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THESIS

OPTIMIZING LONG-TERM CAPITAL PLANNING FOR SPECIAL OPERATIONS FORCES

by

Gretchen M. Radke

June 2015

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The United States Special Operations Command (USSOCOM) J8 directorate is responsible for planning long-range capital expenditure for Special Operations Forces (SOF). In executing its mission as the designer of the future SOF, the USSOCOM J8 uses the Long-Range Capital Planning Toolkit (LRCPT) to compare total obligation authority to projected investments over a 30-year time horizon. The LRCPT allows USSOCOM to change project and resource category parameters to analyze the effects on available procurement and research, development, test, and evaluation allocations. This "what if" analysis allows for course-of-action comparison and helps USSOCOM visualize resource impacts, but the LRCPT does not provide an optimized program portfolio. The goal of this thesis is to improve the LRCPT by developing proof-of-principle optimization models for long-range capital planning. We present three linear optimization models: (1) the Binary Knapsack model, (2) the Weighted Goal Programming model, and (3) the Weighted Goal Programming with Platform Tracking model. These models can be incorporated into the LRCPT to provide USSOCOM with an efficient method for optimizing long-term procurement planning, ensuring there are no SOF capability gaps over the 30-year horizon.

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OPTIMIZING LONG-TERM CAPITAL PLANNING FOR SPECIAL OPERATIONS FORCES

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ABSTRACT

The United States Special Operations Command (USSOCOM) J8 directorate is responsible for planning long-range capital expenditure for Special Operations Forces (SOF). In executing its mission as the designer of the future SOF, the USSOCOM J8 uses the Long-Range Capital Planning Toolkit (LRCPT) to compare total obligation authority to projected investments over a 30-year time horizon. The LRCPT allows USSOCOM to change project and resource category parameters to analyze the effects on available procurement and research, development, test, and evaluation allocations. This "what if" analysis allows for course-of-action comparison and helps USSOCOM visualize resource impacts, but the LRCPT does not provide an optimized program portfolio. The goal of this thesis is to improve the LRCPT by developing proof-of-principle optimization models for long-range capital planning. We present three linear optimization models: (1) the Binary Knapsack model, (2) the Weighted Goal Programming model, and (3) the Weighted Goal Programming with Platform Tracking model. These models can be incorporated into the LRCPT to provide USSOCOM with an efficient method for optimizing long-term procurement planning, ensuring there are no SOF capability gaps over the 30-year horizon.

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LIST OF ACRONYMS AND ABBREVIATIONS

AD	Assessment Directors
ARADA	Anti-armor Resource Allocation Decision Aid
BK	Binary Knapsack
CIPA	Capital Investment Planning Aid
COIN-OR	Computational Infrastructure for Operations Research
DAU	Defense Acquisition University
DOD	Department of Defense
FY	Fiscal Year
FYDP	Future Years Defense Program
GAMS	General Algebraic Modeling System
JCA	Joint Capability Area
JPAT	Joint Platform Allocation Tool
LRCPT	Long-Range Capital Planning Toolkit
MFP	Major Force Program
OSD	Office of the Secretary of Defense
POM	Program Objective Memorandum
PPBE	Planning Programming Budgeting Execution
PPBES-MIS	Planning Programming Budgeting Execution System – Management Information System
RCL	Required Capability List
RDT&E	Research, Development, Test and Evaluation
SCOUT	Space Command Optimizer of Utility Toolkit
SecDef	Secretary of Defense
SOF	Special Operations Forces
StORM	Suite of Resource Models
TOA	Total Obligation Authority
USSOCOM	United States Special Operations Command
VFT	Value Focused Thinking
WGP	Weighted Goal Programming
WGPwPT	Weighted Goal Programming with Platform Tracking

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EXECUTIVE SUMMARY

Since September 11, 2001, Special Operations Forces (SOF) operations have significantly contributed to the accomplishment of United States' strategic and operational objectives as well as global stability at large. SOF operations range from direct action and irregular warfare to humanitarian assistance and relationship building. In order to perform these unconventional missions, SOF units require a variety of unique weapons and equipment. In light of the diminishing Department of Defense (DOD) budget and the Budget Control Act, the United States Special Operations Command (USSOCOM) needs an improved methodology for long-term investment planning in order to ensure there are no SOF capability gaps in the future (Steger, 2015).

The USSOCOM J8 directorate is responsible for determining the appropriate force structure, requirements, and resources for SOF. Currently, the J8 manages long-term procurement planning through its Long-Range Capital Planning Toolkit (LRCPT) (Steger, 2015). The LRCPT views a 30-year horizon at the project level. To accomplish this, the LRCPT extends Program Objective Memorandum budget data plus inflation and includes procurement and research, development, and test and evaluation amounts from known recurring programs (Steger, 2015). The LRCPT allows USSOCOM to change project and resource category parameters in order to analyze the effects on available procurement and research, development, test, and evaluation allocations. It is up to the analyst to manually specify all the proposed details for any given scenario over the entire planning horizon. Although straightforward, this process does not produce an investment strategy that optimizes allocation of procurement money over the entire planning horizon.

This thesis presents proof-of-principle models to improve the LRCPT by incorporating goal programming and optimization. We present three models: (1) the Binary Knapsack (BK) model, which selects the set of projects that has the maximum total value at a portfolio cost no greater than the budget; (2) the Weighted Goal Programming (WGP) model, which chooses an investment strategy that minimizes the total weighted penalty for violating the budget, project procurement, and capability goals; and (3) the Weighted Goal Programming with Platform Tracking (WGPwPT) model,

which builds on the WGP model by examining the projects at the platform level and recommending a yearly investment strategy that minimizes the total weighted penalty for violating budget, procurement, retirement, portfolio value, and platform inventory constraints.

We test our models with a 30-year planning horizon including 68 projects and one category of money. We validate the BK model by analyzing the effect of varying the annual Total Obligation Authority (TOA) budget on the goal of maximizing portfolio value. We perform model runs using three different funding profiles: (1) baseline, (2) constrained budget, and (3) increased budget. Our results for the BK model highlight the fact that even with a five-percent increase in the annual budget, there are still unfunded projects and unspent TOA budget dollars. We conclude that the BK model has limited applications for USSOCOM because of the single objective and absolute budget constraint. The BK model does not provide an adequate solution to the competing objectives of the USSOCOM long-term capital planning problem.

We validate the WGP model by analyzing the effect of varying goal priorities on the goals of maximizing project procurement and portfolio value and minimizing TOA budget violations. We perform model runs using three different goal weighting profiles: (1) baseline, (2) higher priority given to minimizing budget violations, and (3) higher priority given to maximizing portfolio value and project procurement. Our results for the WGP model reveal that, as expected, the best achievement level for each goal is attained when that goal is given priority. Our model results also show the flexibility of the WGP approach by demonstrating the model's ability to allow for tradeoffs between investment goals and priorities. Although the WGP approach is flexible, our WGP model is not capable of taking full advantage of this flexibility because it is restricted to making project level procurement decisions, which forces the model to make all-or-nothing decisions.

Finally, we enhance the WGP to incorporate platform tracking. We examine the projects at the platform level, allowing the model to spread project procurement over several time periods. We validate this model by analyzing the effect of varying goal priorities on the goals of maximizing platform procurement and portfolio value and

minimizing TOA budget violations. We perform model runs using three different goal weighting profiles: (1) baseline, (2) higher priority given to minimizing budget violations, and (3) higher priority given to maximizing portfolio value and platform procurement. The critical insight we find is that this model not only produces the best overall funding strategy; it also balances platform procurement and retirement decisions, maximizing portfolio value. This ensures there are no capability gaps over the planning horizon. Although this enhanced capability comes at the cost of increased computation time, we find the computation time to be acceptable for the problem sizes considered in this thesis.

We conclude that, given adequate computation time, USSOCOM should incorporate the Weighted Goal Programming with Platform Tracking model into the LRCPT as an improved method for examining the impact of long-range investments. This tool will provide USSOCOM with improved visualization of the trade space available for the optimal allocation of procurement money, ensuring there are no SOF capability gaps in the future.

LIST OF REFERENCES

Steger, J. (2015, March). 30-year investment (PROC/RDTE) planning tool. Presented at United States Special Operations Command, MacDill Air Force Base, FL.

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I. INTRODUCTION

In light of the diminishing Department of Defense (DOD) budget and the impending Budget Control Act, the United States Special Operations Command (USSOCOM) needs an improved methodology for long-term investment planning in order to ensure there are no Special Operations Forces (SOF) capability gaps in the future. This thesis presents three proof-of-principle long-range capital planning models designed to improve USSOCOM’s Long-Range Capital Planning Toolkit (LRCPT). The LRCPT is a suite of models developed and used by USSOCOM that allows for a comparison of Total Obligation Authority (TOA) to projected investments over a 30-year time horizon (Steger, 2015). We seek to improve the LRCPT by incorporating goal programming and optimization to determine an optimal long-range investment strategy within TOA guidelines, reducing the necessity to manually prepare complete scenarios.

Chapter II provides background information that impacts the problem. We highlight current planning and programming processes used by USSOCOM, and we discuss related military capital planning applications and optimization methods appearing in the literature. Chapter III presents three optimization models and details the formulation and relevant assumptions for each technique. We compare each model’s performance and present results based on notional data in Chapter IV. Finally, in Chapter V, we offer conclusions and provide recommendations for implementation and further research.

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II. BACKGROUND AND LITERATURE REVIEW

Since September 11, 2001, Congress has approved more than $22.2 billion to buy weapons and equipment for USSOCOM and nearly $70 billion for USSOCOM operations and maintenance (Weisgerber, 2014). This averages out to approximately $6.6 billion a year over the past 14 years. This level of funding was propelled by the ongoing war on terrorism and the rapid growth of military forces to fight two simultaneous wars in Iraq and Afghanistan. However, recent years have seen a shift in defense strategy and the level of funding is likely to decrease in the near future while the demand for SOF capabilities will likely increase. In the January 2012 National Defense Strategy, both the President and the Secretary of Defense (SecDef) called for a shift away from large, conventional forces toward a force that is “agile, flexible, and ready for the full range of contingencies and threats” (DOD, 2012, p. 3). As the DOD faces new challenges during a period of fiscal constraints, USSOCOM will have a critical requirement to effectively and efficiently allocate its resources to meet its global operational demands.

A. HISTORY OF USSOCOM

In October 1986, Congress mandated the creation of USSOCOM in response to significant joint operational failures and the need to address the unconventional threats posed by a world of increasing complexity (Embree, Rockwell, Smith, & Townsend, 2012). In response, DOD activated USSOCOM on April 16, 1987, at MacDill Air Force Base, in Florida.

USSOCOM is one of nine unified combatant commands. USSOCOM provides special operations forces to defend the United States and its interests and to plan and synchronize operations against violent extremist organizations (McRaven, 2014). USSOCOM accomplishes this mission by executing the current Defense Strategic Guidance, which directs the Joint Force of the future to be agile, flexible, and ready, and to use innovative, low-cost, and small-footprint approaches (McRaven, 2014).

USSOCOM has four service components (U.S. Army Special Operations Command, Naval Special Warfare Command, Air Force Special Operations Command,

and Marine Corps Forces Special Operations Command) and eight sub-unified commands (Joint Special Operations Command and the seven Theater Special Operations Commands) (Joint Chiefs of Staff, 2014). USSOCOM is responsible for training SOF to conduct its core activities, including counter-terrorism, unconventional warfare, direct action, special reconnaissance, foreign internal defense, civil affairs, military information support operations, security force assistance, counterinsurgency, hostage rescue and recovery, foreign humanitarian assistance, and counter-proliferation of weapons of mass destruction (Joint Chiefs of Staff, 2014).

USSOCOM is unique from other combatant commands in that it has its own budgetary authority and responsibilities through a specific Major Force Program (MFP-11) in DOD's budget (Embree, Rockwell, Smith, & Townsend, 2012). The significance of MFP-11 funding is that it allows USSOCOM to determine requirements, establish priorities, and develop capabilities for all SOF. This ensures the availability of special operations capabilities while minimizing waste and redundancy (Embree, Rockwell, Smith, & Townsend, 2012). Additionally, because the funds come directly from The Office of the Secretary of Defense (OSD) to USSOCOM rather than to the services, Congress is assured that they will be spent on the SOF programs and requirements (Embree, Rockwell, Smith, & Townsend, 2012).

B. SCALE OF THE PROBLEM

Each fiscal year, the DOD is allocated over $400 billion. USSOCOM's share of the DOD TOA is approximately $10 billion, of which it currently invests approximately $2 billion a year for research, development, and acquisition (USSOCOM, 2014). This corresponds to over $60 billion across a 30-year programming horizon that must be wisely allocated among more than 60 competing candidate projects.

C. OPERATING ENVIRONMENT

The first step in USSOCOM's strategic planning process is to link strategy to capability development and resourcing. In the wake of force reductions, base closures, realignments, and reduced allocation of national resources to the military, the size of the future SOF is in question, mandating a higher priority for research and development activities that maximize the value of each investment dollar spent.

USSOCOM J8 represents the SOF user in the planning and programming of resources. It is the proponent for recommending a long-term investment strategy for resolving shortfalls in SOF capability. J8, in conjunction with the supporting commands, identifies weaknesses to be overcome and doctrinal initiatives that need to be supported, and then, creates a future vision (Embree, Rockwell, Smith, & Townsend, 2012). J8 develops the SOF modernization strategy through the planning and programming portion of DOD's planning, programming, budgeting, and execution (PPBE) process. Figure 1 provides an overview of DOD's PPBE process.

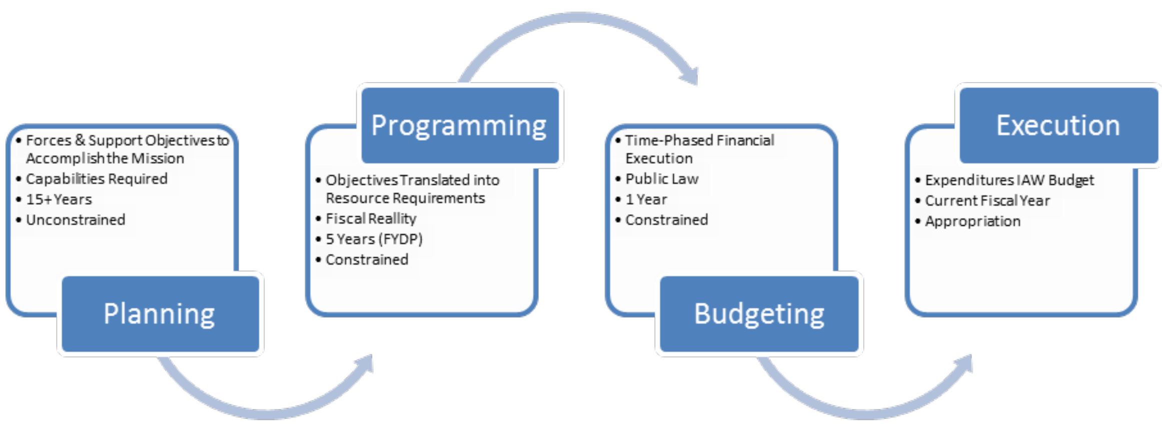

Figure 1. DOD's PPBE process (after Whiteman, 2014).

In order to understand the importance of long-term capital planning and the origin of the inputs to the LRCPT, it is necessary to examine the USSOCOM PPBE process. We first describe a number of key terms and entities.

1. Key Terms

Assessment Directors (AD): USSOCOM J8 Directors responsible for management of capability portfolios. According to Whiteman (2014), the six ADs are:

- Rotary Wing/Maritime
- Fixed Wing
- Manpower
- Forces
- Information and Intelligence Systems
- Special Programs

Appropriation (Resource) Categories: Categories to which Congress assigns dollars. USSOCOM cannot move dollars between appropriation categories without congressional approval (Whiteman, 2014). According to Whiteman (2014), the appropriation categories are:

- RDT&E (research, development, test, and evaluation)
  - RDT&E Activities and Expenses
- Procurement
  - End items whose system cost is at least $100k
  - Spares
  - Labor for certain production related functions
- Operations and Maintenance
  - Replenishment spares
  - Civilian salaries
  - End items whose system cost is at most $100k
  - Training/maintenance costs
- Military construction
  - Construction projects costing at least $750k
- Military personnel
  - Military pay and allowances
  - Permanent change of station moves

USSOCOM Capabilities and Programming Guidance: Provides specific, prioritized guidance for development of the force and enables resourcing to achieve the USSOCOM Commander's priorities (Whiteman, 2014).

Defense Planning Guidance: The Defense Planning Guidance is used to lead the overall PPBE Process (Whiteman, 2014). According to Whiteman (2014), the Defense Planning Guidance reflects the President's National Security Strategy, the SecDef's National Defense Strategy, and the Chairman's National Military Strategy. It also reflects results of the Quadrennial Defense Review and the annual Chairman's Program Recommendations (Whiteman, 2014).

Future Years Defense Program (FYDP): The official record of decisions made regarding the linkage of resources to dollars over a 5 year period (Whiteman, 2014). The FYDP provides a baseline against which future changes will be made.

Fiscal Guidance: The maximum number of dollars USSOCOM can request in each year of the FYDP (Whiteman, 2014). According to Whiteman (2014), fiscal guidance originates in the White House and comes to USSOCOM through OSD and considers geo-political situation, state of the economy, and world affairs.

Major Force Programs (MFP): A database code identifying forces by their capability (Defense Acquisition University [DAU], 2012). According to DAU (2012), there are eleven MFPs:

- Program 1—Strategic forces
- Program 2—General purpose forces
- Program 3—Command, control, communications, intelligence, and space
- Program 4—Mobility forces
- Program 5—Guard and reserve forces
- Program 6—Research and development
- Program 7—Central supply and maintenance
- Program 8—Training, medical, and other general personnel activities
- Program 9—Administration and associated activities
- Program 10—Support of other nations
- Program 11—SOF

PPBE System-Management Information System (PPBES-MIS): DOD management information system (Oracle database) intended to directly support the PPBE process (Whiteman, 2014). This is the database used to submit the Program Objective Memorandum (POM) to OSD.

Program Objective Memorandum (POM): Recommendation to the SecDef on the allocation of resources for proposed programs to achieve assigned missions and objectives (Whiteman, 2014).

POM Sponsors: USSOCOM stakeholders in the POM process (Whiteman, 2014):

- United States Army Special Operations Command
- Naval Special Warfare Command
- Air Force Special Operations Command
- Marine Special Operations Command
- Joint Special Operations Command
- Headquarters USSOCOM Chief of Staff
- USSOCOM Chief Information Officer
- SOF Acquisition, Technology and Logistics

Joint Capability Area (JCA): Collections of like DOD activities functionally grouped to support capability analysis, strategy development, investment decision making, capability portfolio management, and capabilities-based force development and operational planning (DOD, 2010). The JCAs are composed of nine, Tier I core capabilities that are further broken down into 37 Tier II capabilities. Table 1 lists the Tier I and associated Tier II JCAs.

Table 1. Tier I and II JCAs (after "Joint Capability Area," n.d.).

Tier I JCA	Tier II JCA
Force Support	Force Management; Force Preparation; Human Capital Management; Health Readiness
Battlespace Awareness	Planning & Direction; Collection Processing/Exploitation; Analysis, Prediction, & Production; Data Dissemination & Relay
Force Application	Maneuver; Engagement
Logistics	Deployment & Distribution; Supply; Maintain; Logistics Services; Operational Contract Support; Engineering; Base & Installations Support
Command & Control	Organize; Understand; Planning; Decide; Direct; Monitor
Net-Centric	Information Transport; Enterprise Services; Net Management; Information Assurance
Protection	Prevent; Mitigate
Building Partnerships	Communicate; Shape
Corporate Management & Support	Advisory & Compliance; Strategy & Assessment; Information Management; Acquisition; Program, Budget, & Finance

Required Capability List (RCL): SOF capabilities required to conduct core activities. The RCL is comprised of the 37 Tier II Joint Capability Areas (Whiteman, 2014).

Total Obligation Authority (TOA): The amount of dollars USSOCOM is allocated in one fiscal year (Whiteman, 2014).

2. Suite of Resource Models

Suite of Resource Models (StORM) is a collection of analytic models and processes that USSOCOM J8 currently uses to inform resourcing decisions (Whiteman, 2014). According to Whiteman (2014), StoRM is comprised of the RCL Prioritization Tool, Value Focused Thinking (VFT) Model, Sledgehammer, Screwdriver, a voting tool, and an optimization model with various output charts and displays to aid analysis efforts. StORM provides analytic support for the USSOCOM POM build (Whiteman, 2014).

Figure 2 provides a description of the tools and outlines the flow of data between the StORM tools.

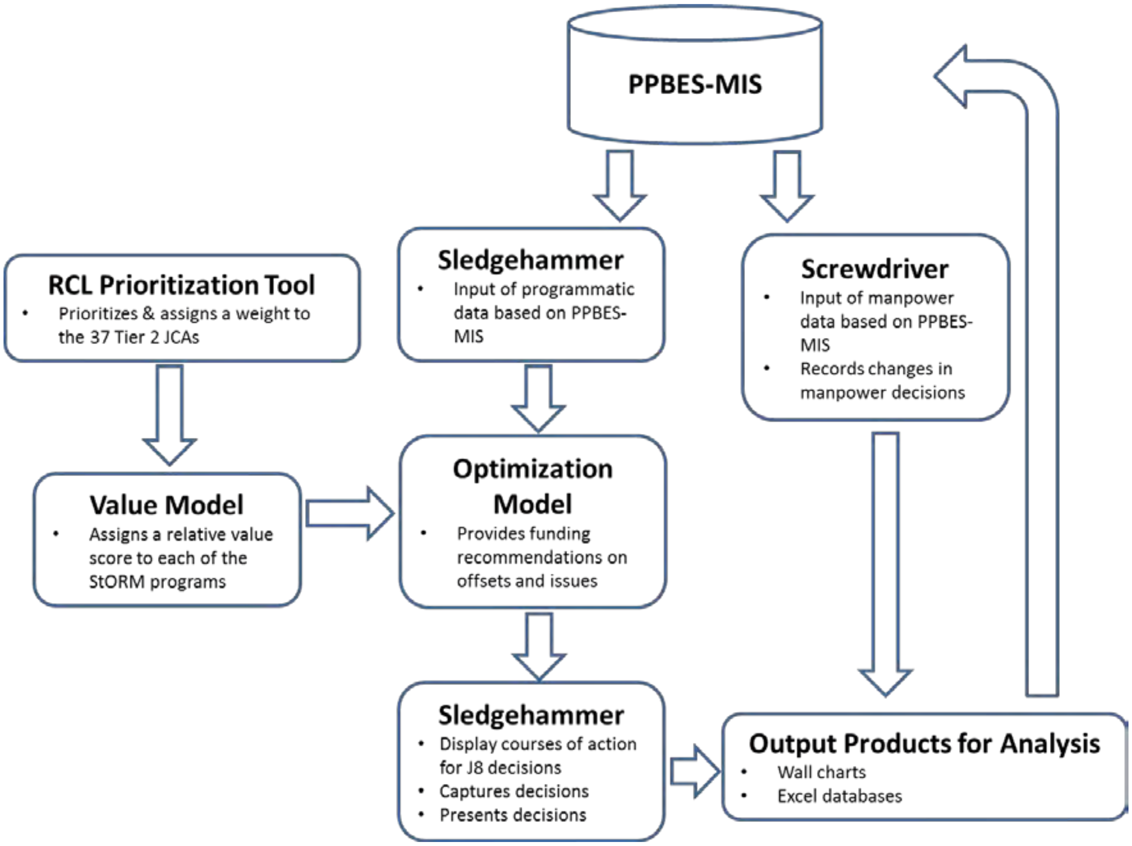

Figure 2. Flow of data between StORM tools (after Whiteman, 2014).

3. USSOCOM POM Process

Multiple inputs are required to build a POM. The baseline comes from the current FYDP (Whiteman, 2014). According to Whiteman (2014), fiscal guidance comes from the Office of Management and Budget/ Office of the Under Secretary of Defense (Comptroller), and the planning and programming guidance comes from OSD and Commander USSOCOM.

The first step in the USSOCOM POM process is the prioritization of capabilities. USSOCOM J8 uses the RCL Prioritization Tool to rank the required capability list and derive a weight to measure the relative importance of various capabilities (Whiteman, 2014). USSOCOM J8 uses the mathematical weights calculated by the RCL Prioritization

Tool as input for the VFT Model. The VFT Model then determines the relative value of the program by assessing it against each of the 37 capability attributes of the required capability list (e.g., “At what level does Program X allow the command to conduct Capability Y?”) (Whiteman, 2014). The scoring criteria are: 9-Critical, 5-Essential, 3-Enhancing, 1-Marginal, and 0-No Contribution (Whiteman, 2014). The VFT Model creates the capabilities-based program list for USSOCOM. The capabilities-based program list is a rank ordered list of programs with mapping of programs to Tier II JCAs (Whiteman, 2014). USSOCOM then publishes this list in the Capabilities and Programming Guidance and uses it as input to the optimization model during resource constraining (Whiteman, 2014).

After USSOCOM publishes the Capabilities and Programming Guidance, SOF Acquisition, Technology and Logistics personnel brief the ADs and components on the current status of the programs (Whiteman, 2014). This brief serves as a baseline review. During the baseline review, USSOCOM J8 uses the voting tool to capture comments and flag programs for further investigation (Whiteman, 2014). According to Whiteman (2014), the Excel-based voting tool gives POM sponsors a method to provide anonymous feedback and vote on issues during their Integrated Concept Team meetings. USSOCOM J8 then consolidates the voting tool results and incorporates the POM sponsor feedback into a dashboard used for reference by the ADs during resource constraining (Whiteman, 2014).

Following the baseline review, USSOCOM J8 builds the POM database. USSOCOM J8 uses Sledgehammer (an Excel-based tool) to create a snapshot of the PPBES-MIS financial database and make recommended funding changes (Whiteman, 2014). Sledgehammer simultaneously displays multiple alternatives to decision-makers and then automatically imports the changes back into the PPBES-MIS (Whiteman, 2014).

USSOCOM then holds Integrated Concept Team meetings. During these meetings, each component briefs its commander’s rank ordered program list and statements of concern and the other POM sponsors brief their issues (Whiteman, 2014).

The last step in the POM build process is resource constraining. This is usually a four-to-six-week process following the Integrated Concept Team meetings, during which the ADs determine which issues will be funded (Whiteman, 2014). USSOCOM J8 also uses the StORM optimization model during resource constraining to quickly determine the impact of changes to program costs, available budgets, dependency of programs, new programs added to the portfolio, and "must-do-it" leadership decisions (Whiteman, 2014).

USSOCOM J8 has successfully applied StORM to build the last three POMs (POM14, POM15, and POM16) (Whiteman, 2014). According to Whiteman (2014), StORM has enabled USSOCOM to resource more effectively by using an analytically rigorous process that is structured, repeatable, transparent, and defendable.

4. USSOCOM LRCPT

In June of 2014, the USSOCOM J8 expressed a need to look further out than the seven year planning horizon of the POM to analyze future capital investment requirements to identify opportunities and risk (Steger, 2015). According to Steger (2015), in August of 2014, the J8 conducted an initial "POM47" (30-year planning horizon) meeting to discuss the task and data collection requirements. Based on the meeting, USSOCOM J8 published the Task Management Tool tasking, requesting data on all recurring investment (procurement and RDT&E) programs (Steger, 2015). By the end of September 2014, the J8 had developed the LRCPT to visualize and analyze program data in accordance with anticipated Task Management Tool responses (Steger, 2015). The LRCPT has allowed them to identify several risk and opportunity areas as well as trends across various USSOCOM portfolios (Steger, 2015).

The LRCPT views a 30-year horizon at the project level and allows for a comparison of TOA to projected investments by recreating projects throughout the 30+ year timeline based on the program's life-cycle (Steger, 2015). According to Steger (2015), LRCPT projects TOA and resource category amounts to reflect anticipated increases and show their effects on available investment money. To accomplish this, LRCPT extends POM data plus inflation and includes procurement and RDT&E amounts

from known, recurring programs (Steger, 2015). The LRCPT allows the user to change project and resource category parameters to analyze their effects, but it is up to the analyst to manually specify all the proposed details for any given scenario over the entire planning horizon. Although straightforward, this process does not produce a project portfolio that maximizes SOF mission capability over the entire planning horizon. Thus, our goal is to improve the LRCPT by incorporating goal programming and optimization to develop a long-range investment strategy.

D. LITERATURE REVIEW

This section provides a brief review of literature relevant to this thesis. We describe related military capital planning applications and optimization methods appearing in the relevant literature.

1. Military Capital Planning

"Since the introduction of goal programming after WWII, the military has used optimization-based planning tools to solve capital planning problems" (Brown, Dell, & Newman, 2004, p. 415). Although the military applications we present in this section vary in complexity, the methods and decision support tools we describe were all developed to solve real-world military problems.

Brown, Clemence, Teufert, and Wood (1991) describe an optimization-based decision support tool, PHOENIX, designed to conduct long term planning for modernizing the U.S. Army's aging helicopter fleet. PHOENIX was used in 1988 to plan the modernization of the Army's helicopter fleet by incorporating: (1) procurement through completely new production lines, (2) procurement through block modification incorporating enhancements, (3) extending the service life of the current helicopters, and (4) retiring obsolete platforms. PHOENIX seeks to optimize the scheduling of these actions by minimizing operating and maintenance costs while maintaining enough helicopters to meet mission requirements, staying under maximum age restrictions, satisfying production and manufacturing requirements, and staying within a reasonable budget. PHOENIX confirmed the necessity to downsize the Army's helicopter fleet, identified inevitable mission area shortfalls, and pointed out that some of the current

platforms were less cost effective than others. PHOENIX was credited with saving the Army's helicopter program by recommending appropriate funding levels and suggesting carefully planned policy constraint violations.

Donahue (1992) presents a multi-objective optimization model to plan the Army's modernization actions. The model maximizes warfighting benefit provided by candidate programs while maintaining mission area balance. The model is constrained by budget, congressionally mandated projects, incremental funding, and program dependencies. The model was implemented by the Army's Training and Doctrine Command as a tool in designing overall optimal Army investment strategies.

Ihde (1995) developed the Anti-armor Resource Allocation Decision Aid (ARADA) to assist the DOD in planning procurement of anti-armor systems. ARADA uses numerical scores to quantify the effectiveness of weapon systems under consideration. It seeks to maximize the effectiveness across selected weapons subject to budget and procurement constraints.

Field (1999) presents an integer-linear program, the Capital Investment Planning Aid (CIPA) to plan Navy force structure over a 25-year horizon. CIPA recommends the optimal yearly force structure (ships) subject to shipyard constraints, budget constraints, total number of ships required, and ship class requirements. Baran (2000) extends CIPA to include additional Navy ship classes, aircraft types, and funding categories. Salmeron, Dell, Brown, and Rowe (2002) further extend CIPA and introduce a graphical user interface to make the system more user friendly for the average analyst.

Newman, Brown, Dell, Giddings, and Rosenthal (2000) and Brown, Dell, Holtz, and Newman (2003) present a mixed integer linear program, the Space Command Optimizer of Utility Toolkit (SCOUT) to plan U.S. Air Force space-related investments over a 25-year horizon. The model recommends a portfolio of new start (concept) systems, current systems, and launches that minimize shortfalls in mission performance, while staying within budget constraints, launcher demand, launcher availability, and adhering to logic rules governing system precedence and dependencies.

Brown, Dell, and Newman (2004) present a succession of mathematical optimization models that can be used to solve long-term military capital planning problems. The models consider an increasingly complex set of embellishments including: multi-year planning horizons, different categories of money, project dependencies and interactions, and retirement decisions.

The Army's Training and Doctrine Command Analysis Center and the Naval Postgraduate School developed an optimization model called the Joint Platform Allocation Tool (JPAT) (Craparo, Smead, & Tabacca, 2013) to determine the optimal reconnaissance and surveillance asset investment portfolio. The model considers cost, performance, production schedules, and mission requirements for current and planned systems. JPAT determines the investment strategy and asset assignment to mission demands that maximizes fulfilling the prioritized mission demand. JPAT also models budgetary considerations by taking into account the costs associated with distribution, maintenance and retirement of systems while staying within a maximum budget.

2. Capital Budgeting Methodologies

The simplest optimization model for capital budgeting problems is formulated using linear integer programming with binary variables. This is a special case of the well-known "knapsack problem" developed by Senju and Toyoda (1968). The linear zero-one or binary knapsack heuristic approach quickly suggests a near-optimal portfolio of proposals from a large number of candidate proposals where choices are restricted by their consumption of a discrete number of limited resources. This binary knapsack model is limited by having a single resource and single objective, though other extensions exist.

Goal programming is used to solve optimization problems with multiple objectives. Rather than optimize a single objective, a goal programming model seeks to achieve a collection of goals (e.g., Ragsdale, 2012). The objective is a general statement that reflects the desires of the decision maker (e.g., minimize cost, maximize profit, maximize portfolio value, etc.) and the "target value is a desired or acceptable level of achievement that the decision maker wants to obtain for the goal" (Ragsdale, 2012, p. 311). Goals are also referred to as elastic constraints, where any over or under

achievement of a stated goal is termed a goal deviation (Ragsdale, 2012). The desire of goal programming is to minimize the deviations.

III. MODELS

We now present three optimization models designed to select an optimal portfolio of investments over a multi-year planning horizon. The first two models produce recommended strategies at the macro (project) level, while the third model provides a recommended investment strategy at the micro (platform) level. The models use the linear zero-one and goal programming approaches covered in Chapter II.

A. BINARY KNAPSACK

Following Brown, Dell, and Newman (2004), the simplest optimization model we develop is the Binary Knapsack (BK) model. This model considers a series of fixed budgets and a set of binary acquisition options, where each option has a value and an associated cost (Brown, Dell, & Newman, 2004, p. 417). It then seeks to maximize the payoff (value) of the projects selected while satisfying all budget constraints over the time horizon. This model is an integer linear program with a single linear inequality constraint with non-negative coefficients (Brown, Dell, & Newman, 2004, p. 417). The advantage of this simple approach is that it quickly selects a portfolio of projects from a large number of candidate projects.

(1) Sets and Indices

$t \in T$ time periods in the planning horizon {2016, 2017, …}.

$p \in P$ projects available for acquisition {proj1, proj2, …}.

(2) Data [units]

$budget_t$ available procurement and RDT&E funding in period *t* [$].

$fixedcontrib_p$ fixed contribution of project *p* toward the portfolio value [value units].

$fixedcost_{pt}$ fixed cost of selecting project p in period t [$].

(3) Decision Variables

$SELECT_{pt}$ 1 if project p is chosen, 0 otherwise [binary].

(4) Formulation

$$\max \sum_{t,p} fixedcontrib_p SELECT_{pt} \tag{1.1}$$

$$\text{s.t. } \sum_{p} \left(fixedcost_{pt} SELECT_{pt} \right) \leq budget_t \quad \forall t \tag{1.2}$$

$$SELECT_{pt} \in \{0,1\} \qquad \forall p,t \tag{1.3}$$

(5) Explanation

The objective function 1.1 seeks to maximize the net present value of the total portfolio over a 30-year time horizon. It sums the fixed contribution of each project selected in each time period.

Constraint set 1.2 limits expenditures in a year to the annual budget.

Constraint set 1.3 requires the decision variables to be binary.

B. WEIGHTED GOAL PROGRAMMING

Our second model is the linear Weighted Goal Programming (WGP) model. The decision of whether to select a project for procurement in a given year is governed by a binary decision variable. The model uses elastic constraints and a penalty function. The WGP model seeks to minimize the penalties associated with violating the budget, projects required, and portfolio value goals, where deviations are measured as a percentage of the target level.

(1) Sets and Indices

$t \in T$ time periods in the planning horizon {2016, 2017, …}.

$p \in P$ projects available for acquisition {proj1, proj2, …}.

(2) Data [units]

$budget_t$ available procurement and RDT&E funding in period t [$].

$fixedcontrib_p$ fixed contribution of project *p* toward the portfolio value [value units].

$fixedcost_{pt}$ fixed cost of selecting project p in period t [$].

$avail_t$ desired number of projects to procure in period *t* [*p*-units].

$value_t$ desired portfolio value in period *t* [value units].

$wghtprojund_t$ penalty for selecting less than the desired quantity of projects in period *t* [penalty units].

$wghtprojovr_t$ penalty for selecting more than the desired quantity of projects in period *t* [penalty units].

$wghtundbdgt_t$ penalty for being under budget in period *t* [penalty units].

$wghtovrbdgt_t$ penalty for being over budget in period *t* [penalty units].

$wghtvalund_t$ penalty for being under the target portfolio value in period *t* [penalty units].

$wghtvalovr_t$ penalty for being over the target portfolio value in period *t* [penalty units].

(3) Decision Variables

$SELECT_{pt}$ 1 if project *p* is chosen, = 0 otherwise [binary].

$QUNDER_t$ number of projects under goal during period *t* [*p*-units].

$QOVER_t$ number of projects over goal during period *t* [*p*-units].

$BUNDER_t$ amount of available Proc/RDT&E funding not spent in period *t* [$].

$BOVER_t$ amount of Proc/RDT&E spending over budget in period *t* [$].

$VUNDER_t$ portfolio value under goal during period *t* [value units].

$VOVER_t$ portfolio value over goal during period t [value units].

(4) Formulation

$$\min \sum_t \frac{wghtprojovr_t}{avail_t} QOVER_t + \frac{wghtprojund_t}{avail_t} QUNDER_t$$

$$+\frac{wghtundbdgt_t}{budget_t} BUNDER_t + \frac{wghtovrbdgt_t}{budget_t} BOVER_t \tag{1.4}$$

$$+\frac{wghtvalovr_t}{value_t} VOVER_t + \frac{wghtvalund_t}{value_t} VUNDER_t$$

$$\text{s.t. } \sum_p SELECT_{pt} + QUNDER_t - QOVER_t = avail_t \qquad \forall t \tag{1.5}$$

$$\sum_p fixedcost_{pt} SELECT_{pt} + BUNDER_t - BOVER_t = budget_t \qquad \forall t \tag{1.6}$$

$$\sum_p fixedcontrib_p SELECT_{pt} + VUNDER_t - VOVER_t = value_t \qquad \forall t \tag{1.7}$$

$$SELECT_{pt} \in \{0,1\} \qquad \forall p,t \tag{1.8}$$

$$QUNDER_t, QOVER_t, BUNDER_t, BOVER_t, VUNDER_t, VOVER_t \geq 0 \qquad \forall t \tag{1.9}$$

(5) Explanation

The objective function 1.4 seeks to minimize the total weighted and deviations from the model goals over the time horizon. It sums the deviations for the budget, project quantity and portfolio value constraints, where each is measured as a percentage of the constraint right hand side.

Constraint sets 1.5, 1.6, and 1.7 are the elastic constraints allowing for under-or-over-achievement of budget, quantity, and value goals, and recording deviations from these goals.

Constraint set 1.8 requires the project selection decision variables to be binary.

Constraint set 1.9 requires the goal deviation decision variables to be nonnegative.

C. WGP WITH PLATFORM TRACKING

The third model we develop is a WGP model with platform tracking (WGPwPT). The WGPwPT model uses integer decision variables, elastic constraints and a penalty function. The model seeks to minimize the penalties associated with violating the budget, procurement, retirement, portfolio value, and platform inventory requirements. This

model builds on the previous WGP model by replacing the binary project decision variables with integer decision variables for platform procurement and retirement decisions. In essence, where the WGP model purchases platforms “in bulk” via projects, the WGPwPT model enjoys the additional flexibility of purchasing platforms one-by-one. This, combined with the elastic constraints, allows for a greater set of solutions to be considered. Although our model allows flexibility in the number of platforms purchased, it is also possible to incorporate a minimum purchase amount in the event that a project is undertaken.

(1) Sets and Indices

$t \in T$ time periods in the planning horizon {2016, 2017, …}.

$p \in P$ projects available for acquisition {proj1, proj2, …}.

(2) Data [units]

$budget_t$ available procurement and RDT&E funding in period *t* [$].

$value_t$ desired total portfolio value in period *t* [value units].

$portfolio_t$ desired number of platforms in portfolio in period *t* [value units].

$startinv_p$ initial inventory of platforms of project *p* [*p*-units].

$fixedcost_{pt}$ fixed cost of procuring one platform of project *p* in period *t* [$].

$fixedcontrib_p$ fixed contribution of one platform of project *p* toward the portfolio value [value units].

$procaspire_p$ desired number of platforms of project *p* to procure [*p*-units].

$retaspire_p$ desired number of platforms of project *p* to retire [*p*-units].

$reqinventory_{pt}$ quantity of platforms of project *p* required in portfolio in period *t* [*p*-units].

$authinventory_{pt}$ maximum number of platforms of project p allowed in inventory in period t [p-units].

$maxprojproc_{pt}$ maximum number of platforms of project p allowed to be procured in period t [p-units].

$maxprojret_{pt}$ maximum number of platforms of project p allowed to be retired in period t [p-units].

$wghtprocund_{p}$ penalty for selecting less than the desired quantity of platforms of project p [penalty units].

$wghtprocovr_{p}$ penalty for procuring more than the desired quantity of platforms of project p [penalty units].

$wghtretund_{p}$ penalty for retiring more than the desired quantity of platforms of project p [penalty units].

$wghtretovr_{p}$ penalty for retiring less than the desired quantity of platforms of project p [penalty units].

$wghtundbdgt_{t}$ penalty for being under budget in period t [penalty units].

$wghtovrbdgt_{t}$ penalty for being over budget in period t [penalty units].

$wghtportund_{t}$ penalty for being under the desired quantity of platforms in portfolio for period t [penalty units].

$wghtportovr_{t}$ penalty for being over the desired quantity of platforms in portfolio for period t [penalty units].

$wghtvalund_{t}$ penalty for being under the target portfolio value in period t [penalty units].

$wghtvalovr_{t}$ penalty for being over the target portfolio value for period t [penalty units].

(3) Decision Variables

$PROC_{pt}$ number of platforms of project p to procure in period t [p-units].

$RETIRE_{pt}$ number of platforms of project p to retire in period t [p-units].

$INVENTORY_{pt}$ inventory of platforms of project p in period t [p-units].

$PUNDER_{p}$ number of platforms of project p under procurement target [p-units].

$POVER_{p}$ number of platforms of project p over procurement target [p-units].

$RUNDER_{p}$ number of platforms of project p under retirement target [p-units].

$ROVER_{p}$ number of platforms of project p over retirement target [p-units].

$QUNDER_{t}$ number of platforms under total inventory requirement in period t [p-units].

$QOVER_{t}$ number of platforms over total inventory requirement in period t [p-units].

$BUNDER_{t}$ amount of available Proc/RDT&E funding not spent in period t [$].

$BOVER_{t}$ amount of Proc/RDT&E spending over budget in period t [$].

$VUNDER_{t}$ portfolio value under goal during period t [value units].

$VOVER_{t}$ portfolio value over goal during period t [value units].

(4) Formulation

$$\min \sum_t \frac{wghtportund_t}{portfolio_t} QUNDER_t + \frac{wghtportovr_t}{portfolio_t} QOVER_t$$
$$+ \frac{wghtundbdgt_t}{budget_t} BUNDER_t + \frac{wghtovrbdgt_t}{budget_t} BOVER_t$$
$$+ \frac{wghtvalund_t}{value_t} VUNDER_t + \frac{wghtvalovr_t}{value_t} VOVER_t \tag{1.10}$$
$$+ \sum_p \frac{wghtprocund_p}{procaspire_p} PUNDER_p + \frac{wghtprocovr_p}{procaspire_p} POVER_p$$
$$+ \frac{wghtretund_p}{retaspire_p} RUNDER_p + \frac{wghtretovr_p}{retaspire_p} ROVER_p$$

$$\text{s.t. } \sum_t PROC_{pt} + PUNDER_p - POVER_p = procaspire_p \qquad \forall p \tag{1.11}$$
$$\sum_t RETIRE_{pt} + RUNDER_p - ROVER_p = retaspire_p \qquad \forall p \tag{1.12}$$
$$\sum_p fixedcost_{pt} PROC_{pt} + BUNDER_t - BOVER_t = budget_t \qquad \forall t \tag{1.13}$$
$$\sum_p fixedcontrib_p INVENTORY_{pt} + VUNDER_t - VOVER_t = value_t \qquad \forall t \tag{1.14}$$
$$\sum_p INVENTORY_{pt} + QUNDER_t - QOVER_t = \sum_p reqinventory_{pt} \qquad \forall t \tag{1.15}$$
$$reqinventory_{pt} \le INVENTORY_{pt} \le authinventory_{pt} \qquad \forall p,t \tag{1.16}$$
$$RETIRE_{pt} \le maxprojret_{pt} \qquad \forall p,t \tag{1.17}$$
$$PROC_{pt} \le maxprojproc_{pt} \qquad \forall p,t \tag{1.18}$$
$$INVENTORY_{p,2016} = startinv_p + PROC_{p,2016} - RETIRE_{p,2016} \qquad \forall p \tag{1.19}$$
$$INVENTORY_{pt} = INVENTORY_{p,t-1} + PROC_{pt} - RETIRE_{pt} \qquad \forall p, t > 2016 \tag{1.20}$$
$$PROC_{pt}, RETIRE_{pt}, INVENTORY_{pt} \ge 0 \text{ and integer} \qquad \forall p,t \tag{1.21}$$
$$QUNDER_t, QOVER_t \ge 0 \text{ and integer} \qquad \forall t \tag{1.22}$$
$$VUNDER_t, VOVER_t, BUNDER_t, BOVER_t \ge 0 \qquad \forall t \tag{1.23}$$
$$PUNDER_p, POVER_p, RUNDER_p, ROVER_p \ge 0 \qquad \forall p \tag{1.24}$$

(5) Explanation

The objective function 1.10 seeks to minimize the total weighted deviations of the budget, procurement, retirement, value and portfolio inventory goals over the time horizon. Each goal has an associated non-negative elastic variable that takes on the positive magnitude of deviation when the constraint is violated.

Constraint sets 1.11, 1.12, 1.13, 1.14, and 1.15 are the elastic constraints allowing for under-or-over-achievement of procurement, retirement, budget, portfolio value, and inventory goals, and recording deviations from these goals.

Constraint set 1.16 requires the current inventory of platforms be greater than or equal to the desired amount and less than or equal to the authorized amount.

Constraint set 1.17 requires the retirement amounts remain within allowable maximum yearly platform limits.

Constraint set 1.18 requires the procurement amounts remain within allowable maximum yearly platform limits.

Equation 1.19 establishes the inventory of available platforms in year one.

Equation 1.20 counts the number of platforms of type p available in year t.

Constraint sets 1.21, 1.22, 1.23, and 1.24 require the procurement, retirement, and goal deviation decision variables to be nonnegative.

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IV. RESULTS

A. MODEL IMPLEMENTATION

We implement the models in Microsoft Excel using the OpenSolver add-in (Mason & Dunning, 2010) with Computational Infrastructure for Operations Research (COIN-OR) solver (“OpenSolver for Excel,” 2015) and in the General Algebraic Modeling System (GAMS) (GAMS, 2015) with the CPLEX solver, Version 24.2.2 (GAMS-CPLEX, n.d.). We executed the models on a personal laptop with an Intel Core i7-4700MQ processor with 8.0 GB of RAM.

For similarly scoped problem instances, the models range in complexity from the BK model having 2,040 binary decision variables and 30 constraints to the WGPwPT model having 4,412 integer decision variables, 120 continuous variables, and 8,386 constraints. Table 2 provides a description and overview of the complexity of each of the models.

Table 2. Summary of model complexity.

Model	Description	Decision Variables	Constraints
BK	Linear Zero-One Maximize Portfolio Value Strict Budget Constraint Project Level	2,040 (Binary)	30
WGP	Weighted Goal Programming Minimize Penalty for Constraint Violations Elastic Constraints Project Level	2,040 (Binary) 180 (Continuous)	90
WGPwPT	Weighted Goal Programming Procurement and Retirement Tracking Minimize Penalty for Constraint Violations Elastic Constraints Platform Level	4,412 (Integer) 120 (Continuous)	8,386

Model solution times vary between models and solver used. The BK model solution times average 0.19 seconds using Excel and 0.12 seconds using GAMS, both

with an optimality gap of 0%. The WGP model solution times average 0.74 seconds using Excel and 0.17 seconds using GAMS. For the WGP, we specify optimality gaps from 0% to 1%.. The WGPwPT model solution times range from 0.92 to 11.01 seconds using Excel and 0.12 seconds to 0.94 seconds using GAMS. We use optimality gaps ranging from 0% to 3% for the WGPwPT model. We conclude that even though Excel OpenSolver provides a slightly longer solution time, it is the preferred solver platform because of its zero cost and compatibility with USSOCOM's current LRCPT. We use the results produced by Excel for the remaining analysis presented in this chapter. Table 3 shows a summary of the solution times and optimality gaps for the individual model runs.

Table 3. Model solution times and optimality gaps.

	Excel OpenSolver (COIN-OR)		**GAMS (CPLEX)**	
Model and Instance	Solution Time (seconds)	Optimality Gap	Solution Time (seconds)	Optimality Gap
BK (Baseline)	0.23	0%	0.13	0%
BK (Reduced Budget)	0.21	0%	0.11	0%
BK (Increased Budget)	0.14	0%	0.11	0%
WGP (Baseline)	0.55	0%	0.16	0%
WGP (Min. Budget)	1.62	1%	0.19	1%
WGP (Max. Value)	0.04	0%	0.16	0%
WGPwPT (Baseline)	5.73	1%	0.41	1%
WGPwPT (Min. Budget)	11.01	3%	0.94	3%
WGPwPT (Max. Value)	0.92	0%	0.12	0%

B. BK MODEL

We use a 30-year time horizon and 68 projects. This results in 2,040 binary decision variables for procurement decisions and 30 annual budget constraints.

1. Data

Procurement Cost: We use notional estimates for project procurement costs. These costs represent total money budgeted for project procurement and RDT&E in a

given year. The costs are budgeted over the 30-year planning horizon with no distinction between procurement and RDT&E amounts. We use a project cost of zero to represent years with no procurement possible. This data is provided in Appendix A.

Budget: We use notional TOA budget estimates for each year in the 30-year planning horizon. These amounts are provided in Appendix B. The TOA budget for the first five years of the planning horizon is fixed to reflect the FYPD. Yearly budget estimates for the following 25 years are based on USSOCOM current MFP-11 procurement and RDT&E TOA estimates adjusted for inflation.

Project Value: We use notional project values determined using Excel's built-in random number generator. We randomly generate numbers between 0 and 5 with values summing to 100. The values are held constant for the entire 30-year planning horizon. These values are provided in Appendix C.

2. Analysis of Results

We validate the BK model by analyzing the effect of varying the annual TOA budget on the goal of maximizing portfolio value.

In capital budgeting, the money budgeted for each year tends to be the most influential model parameter. Therefore, to examine the maximum return on USSOCOM's investment dollars, we perform model runs using three different funding profiles. The baseline case represents the original TOA estimates. We conduct the second run with a constrained budget consisting of a 5% decrease from the baseline for each of the years six through thirty. For the third run, we increase the baseline budget by 5% for years six through thirty.

The resulting outcomes for each of the runs, as well as the percentage of TOA spent and projects funded are shown in Table 6. As the table indicates, the model is unable to spend 100% of the TOA in any scenario due to the binary nature of its decisions. However, it is able to spend more money when available, and this translates into a larger percentage of projects funded.

Table 4. Results for BK model varying TOA budget.

Metric	Baseline	Reduced TOA	Increased TOA
Total Portfolio Value (Maximum Possible: 3000)	2982	2975.3	2987.7
Percentage of TOA Spent	96.9%	97.3%	95.5%
Percentage of Projects Funded	95.8%	94.7%	96.6%

Our analysis of the investment strategy recommended by the BK baseline model reveals large TOA under-expenditures in FY16, FY28, FY30, and FY31 accounting for 65% of the $2.2 million of TOA that is unspent over the 30-years. The model recommends not funding 70 projects. Figure 3 provides a summary of the BK baseline TOA spending results and Figure 4 shows the BK baseline project funding results.

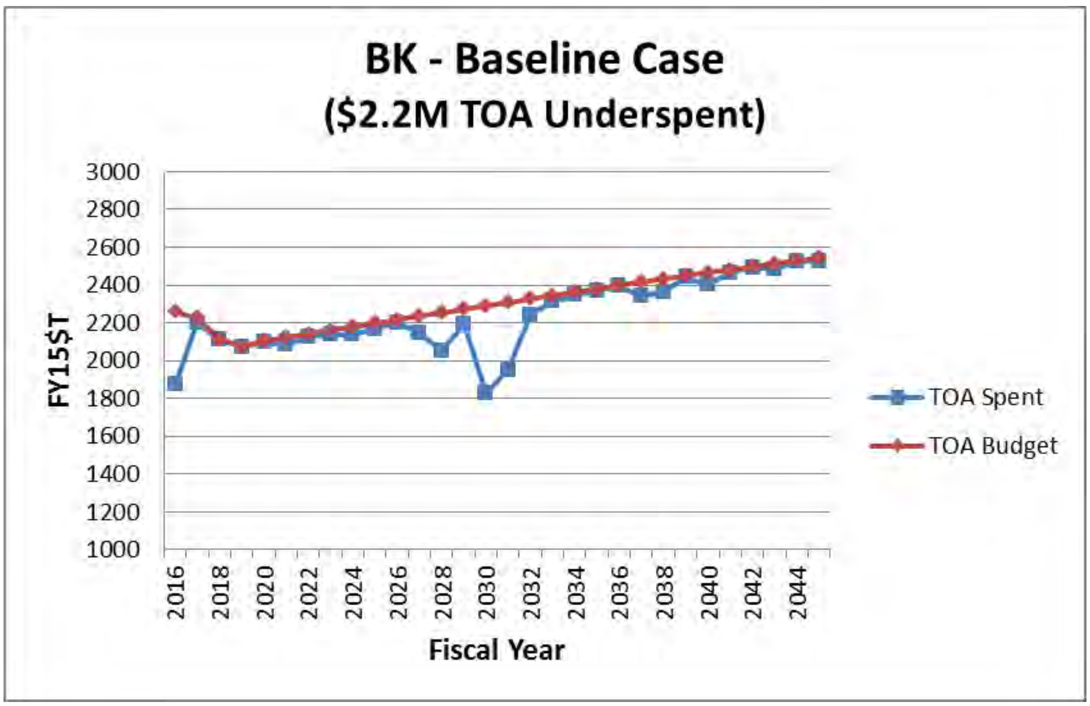

Figure 3. TOA spending for the BK baseline model.

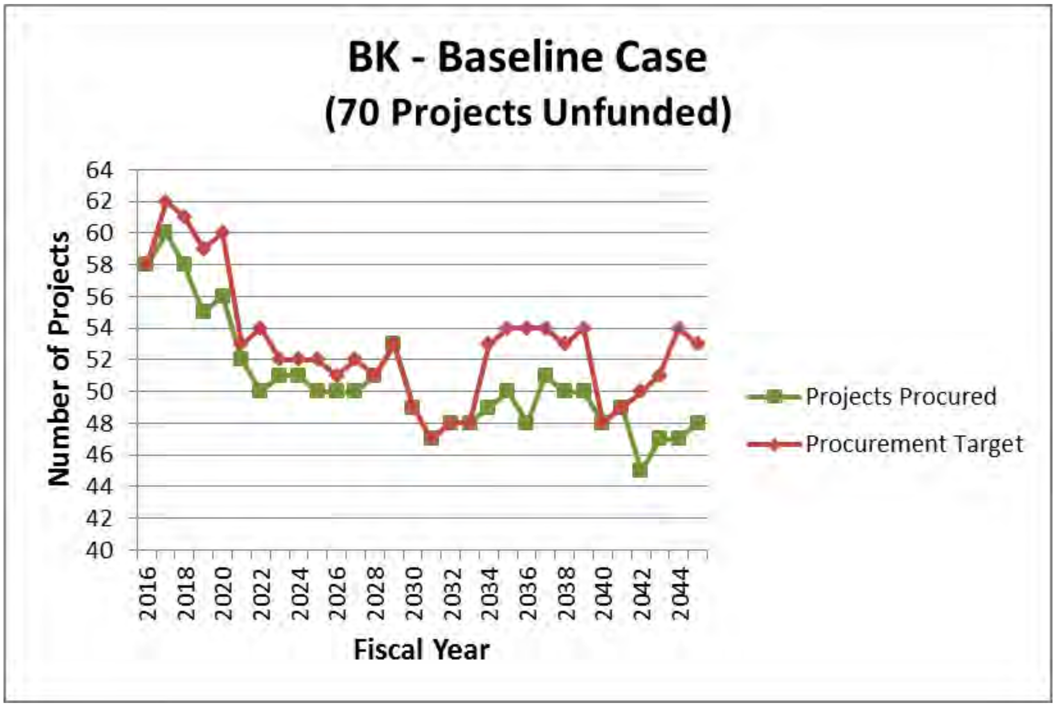

Figure 4. Project funding for the BK baseline model.

When we reduce the budget by 5%, the BK model produces a total TOA under-expenditure of $1.8 million over the 30-year planning horizon. This comes at a cost of not funding 84 projects, 14 more than the baseline. Figure 5 shows the TOA spending results for the BK reduced budget instance. Figure 6 shows the project funding results.

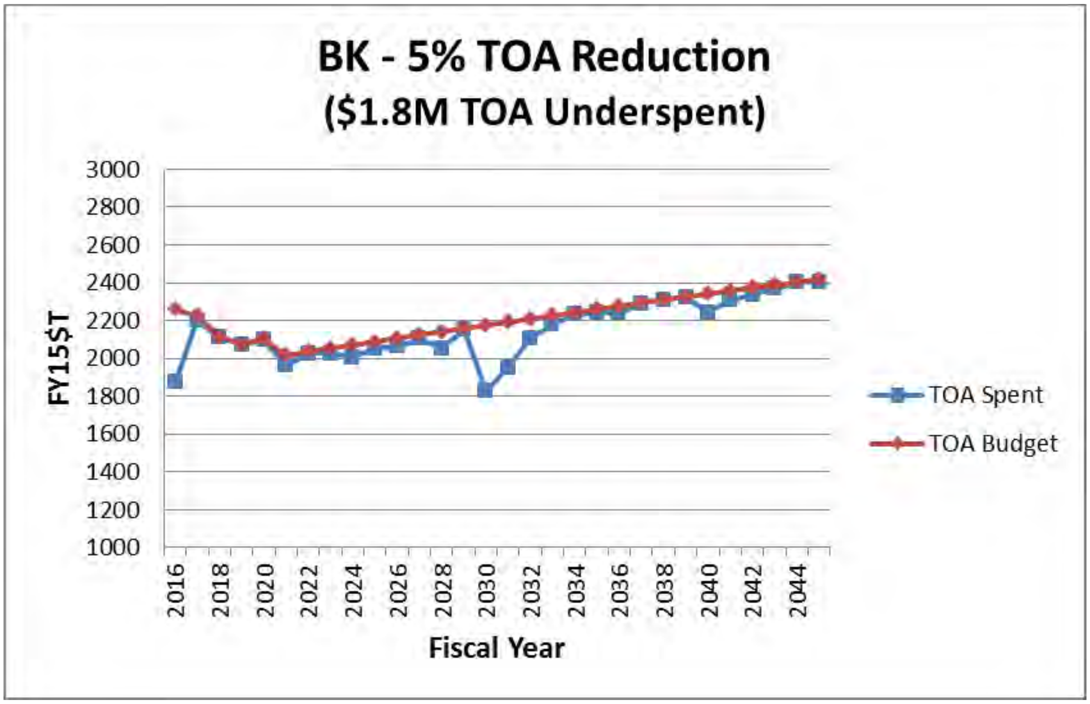

Figure 5. TOA spending for the BK reduced budget model.

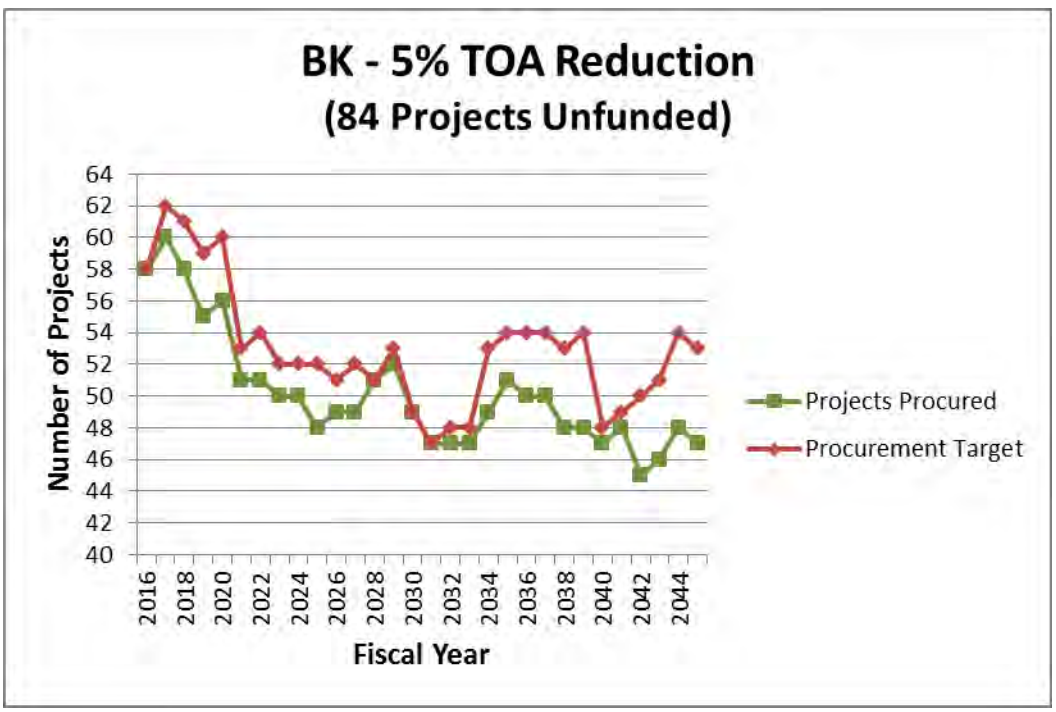

Figure 6. Project funding for the BK reduced budget model.

When we increase the budget by 5%, the BK model produces a total TOA under-expenditure of $3.23 million over the 30-year planning horizon. This is an increase of over $1 million over the BK baseline. The increase in funding still results in 54 project requirements not funded over the 30 years, an improvement of only 16 projects from the baseline. Figure 7 shows the TOA spending results for the BK increased budget model. Figure 8 shows the project funding results.

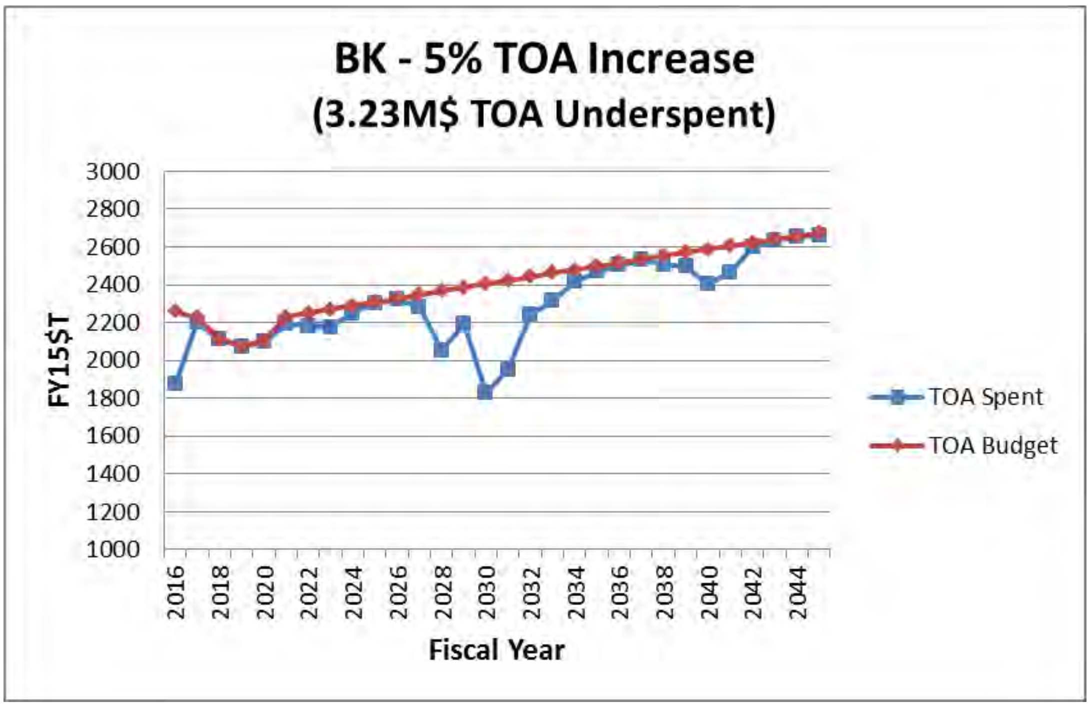

Figure 7. TOA spending for the BK increased budget model.

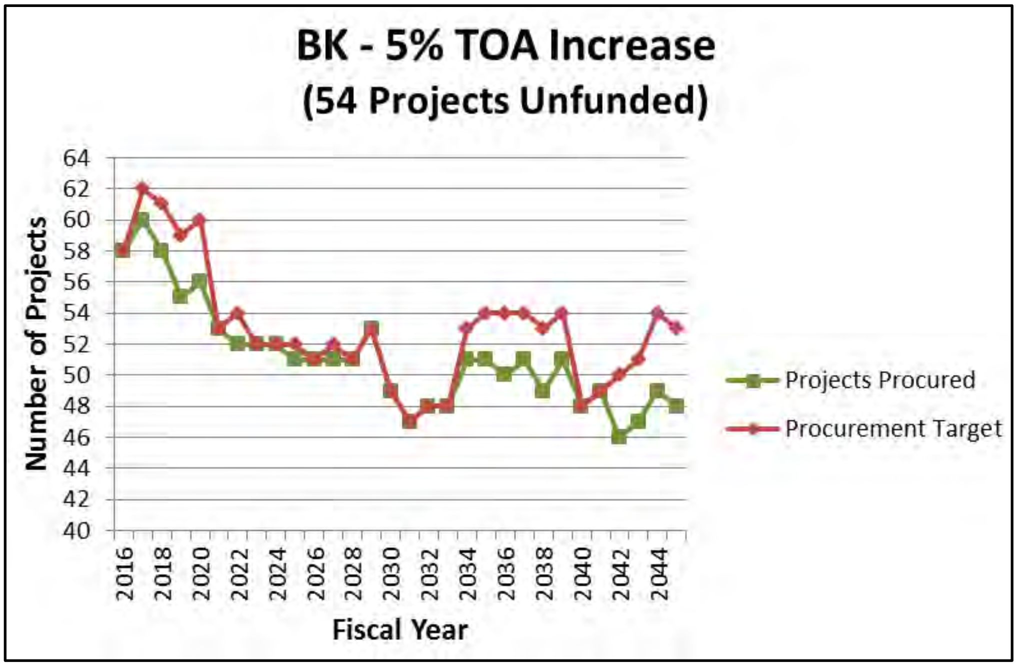

Figure 8. Project funding for the BK increased budget model.

Our results from varying the budget for the BK model highlight the interesting fact that increasing the TOA budget still results in a significant number of unfunded projects and a $1.03 million increase in unspent TOA. It is also important to note that even though increasing the budget produces the highest portfolio value of 2,987.7 out of 3,000, this is only slightly better than the portfolio values of 2,982 and 2,975 produced by the baseline and reduced budget run, respectively.

C. WGP MODEL

To exercise the WGP model, we again use a 30-year time horizon and 68 projects. This results in 2,040 binary decision variables for procurement decisions, 180 non-negative decision variables for goal deviations (60 each for required projects, budget, and portfolio value), and 90 elastic constraints (30 each for required projects, budget, and portfolio value).

1. Data

Procurement Cost: We use the same procurement cost data for projects that we used for the BK model. This data is provided in Appendix A.

Budget: We use the same TOA budget data that we used for the BK model. These amounts are shown in Appendix B.

Project Values: We use the same randomly generated project values that we used for the BK model. These values are shown in Appendix C.

2. Analysis of Results

We validate the WGP model by analyzing the effect of varying the goal priorities on the goals of maximizing portfolio value, minimizing budget violations, and maximizing projects funded. The metrics we used to determine the level of achievement for each of the goals is defined in Table 5.

Table 5. Metrics for WGP and WGPwPT models.

Goal	Metric
Maximize Portfolio Value	Total Portfolio Value (Maximum Possible: 3,000)
Minimize TOA Budget Violations	Percentage of Budget Violations
Maximize # of Funded Projects	Percentage of Funded Projects

The power of the WGP model is found in the decision maker's ability to assign weights to goals. The decision maker can assess the goal priorities and establish penalties associated with violations of the budget, project quantity, and portfolio value constraints. Therefore, to examine the performance of the WGP model, we vary the goal priorities. We make three model runs: (1) a baseline run with all goals weighted equally in terms of percent deviation from the aspiration level, (2) a run giving higher priority to minimizing TOA violations, and (3) a run giving higher priority to maximizing projects procured and portfolio value. For each run, we give the prioritized goals a weight of 10 and the other goals a negligible weight of .001. We use the original baseline budget and hold all other

model parameters constant. The resulting objective values for each of the runs are shown in Table 6.

Table 6. Results for WGP model varying goal priorities.

Metric	Baseline Goals Weighted Equally	Minimize Budget Violations	Maximize Portfolio Value
Total Portfolio Value (Maximum Possible: 3000)	2974.4	2960.65	3000
Percentage of TOA Violations	2.79%	2.43%	14.03%
Percentage of Funded Projects	97.36%	95.66%	100%

Our analysis of the investment strategy recommended by the WGP baseline model reveals large TOA under-expenditures in FY16, FY28, FY30, and FY31 accounting for 73% of the $1.93 million TOA violation over 30 years. This is an improvement of $270 thousand over the BK baseline model, which is to be expected since the BK model was not attempting to spend as much money as possible. The WGP baseline model recommends not funding 42 projects, an improvement of 28 projects over the BK baseline model. Although the WGP model produces improved results for both TOA spent and projects funded, we see a 7.6 unit drop in overall portfolio value from the BK baseline model. Figures 9 and 10 provide a summary of the results for the WGP baseline model.

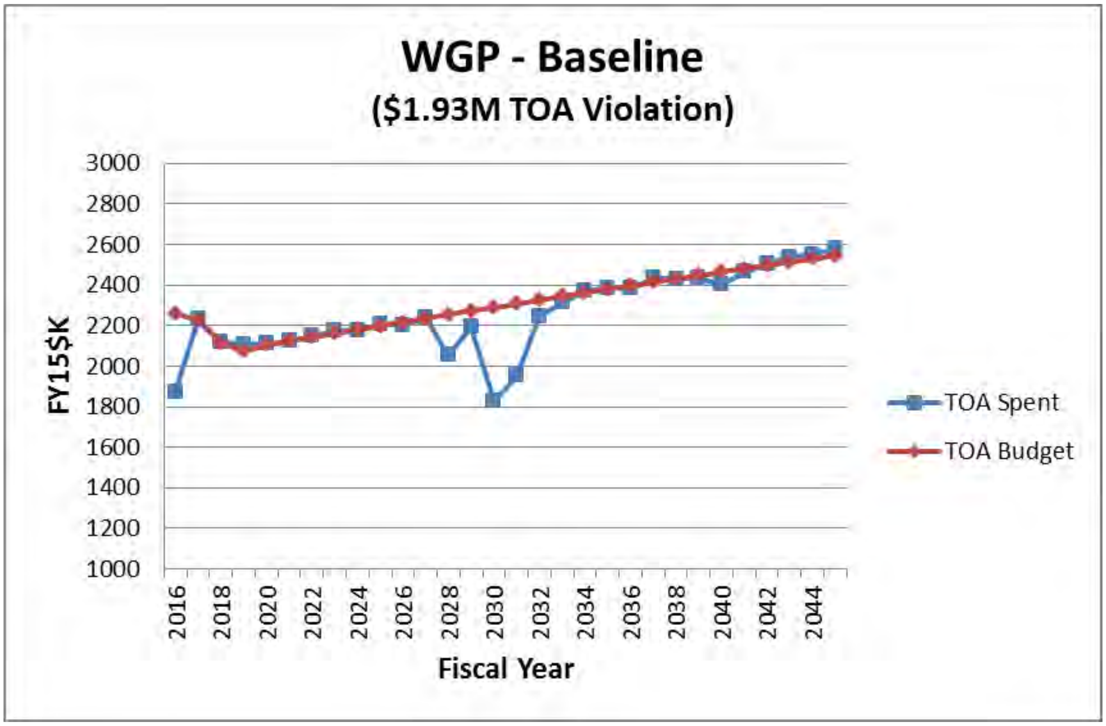

Figure 9. TOA spending for WGP baseline model weighting all goals equal.

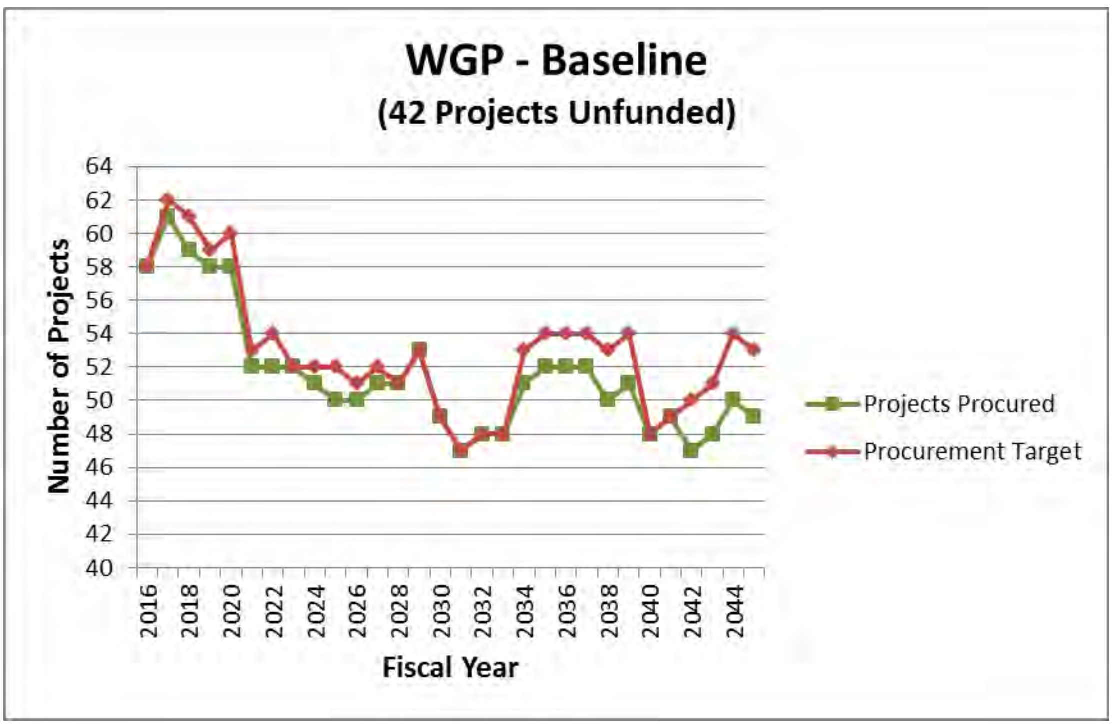

Figure 10. Project funding for WGP baseline model weighting all goals equal.

When we prioritize the goal to minimize budget violations, the WGP model produces a total TOA violation of $1.69 million over the 30-year planning horizon. This is an improvement of $240 thousand over the WGP baseline, but comes at a cost of not funding 69 projects, 27 more than the WGP baseline. Figures 11 and 12 show the TOA spending and project funding results for the WGP model minimizing budget violations.

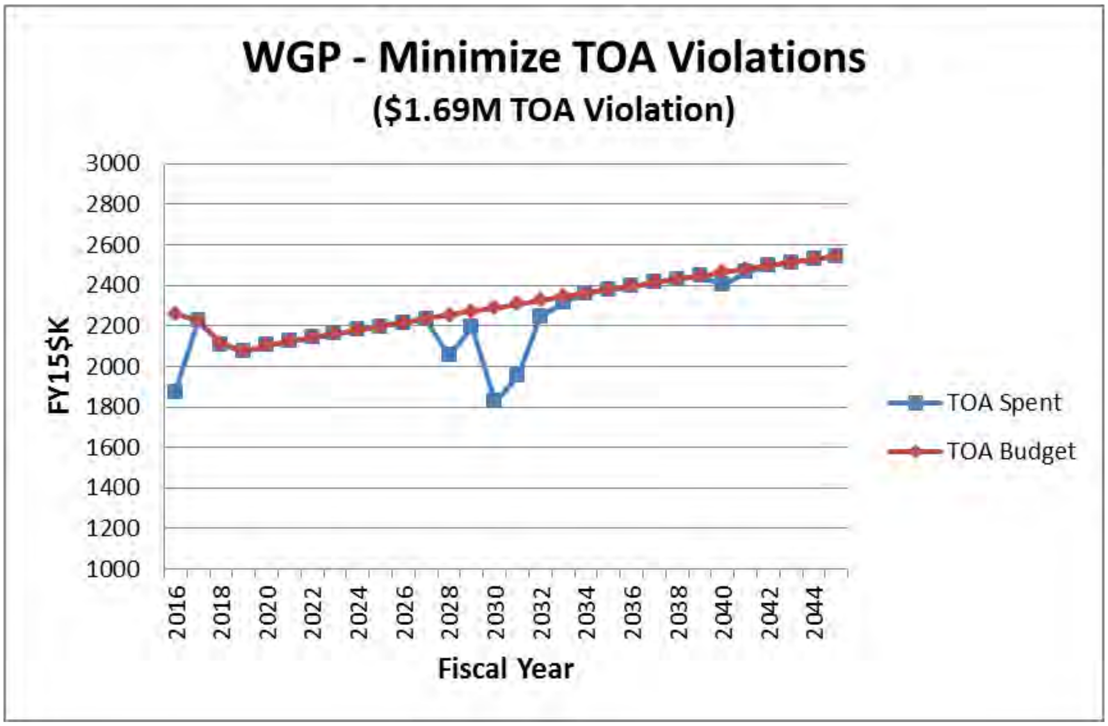

Figure 11. TOA spending for the WGP model minimizing budget violations.

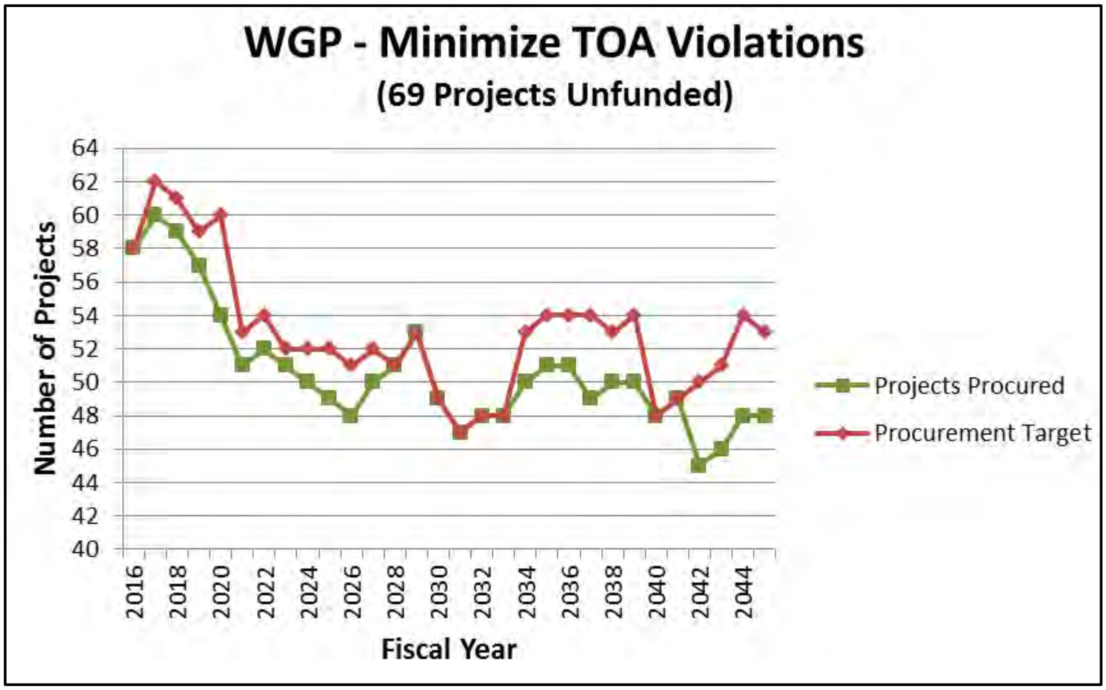

Figure 12. Project funding for the WGP model minimizing budget violations.

When we prioritize the goals to maximize portfolio value and project procurement, the WGP model produces a total TOA budget violation of \$9.72 million over the 30-year planning horizon. This is an increase of \$7.79 million over the WGP baseline. The increase in TOA allows for all of the projects to be procured. Figure 13 shows the TOA spending results for the WGP model maximizing portfolio value and project procurement.

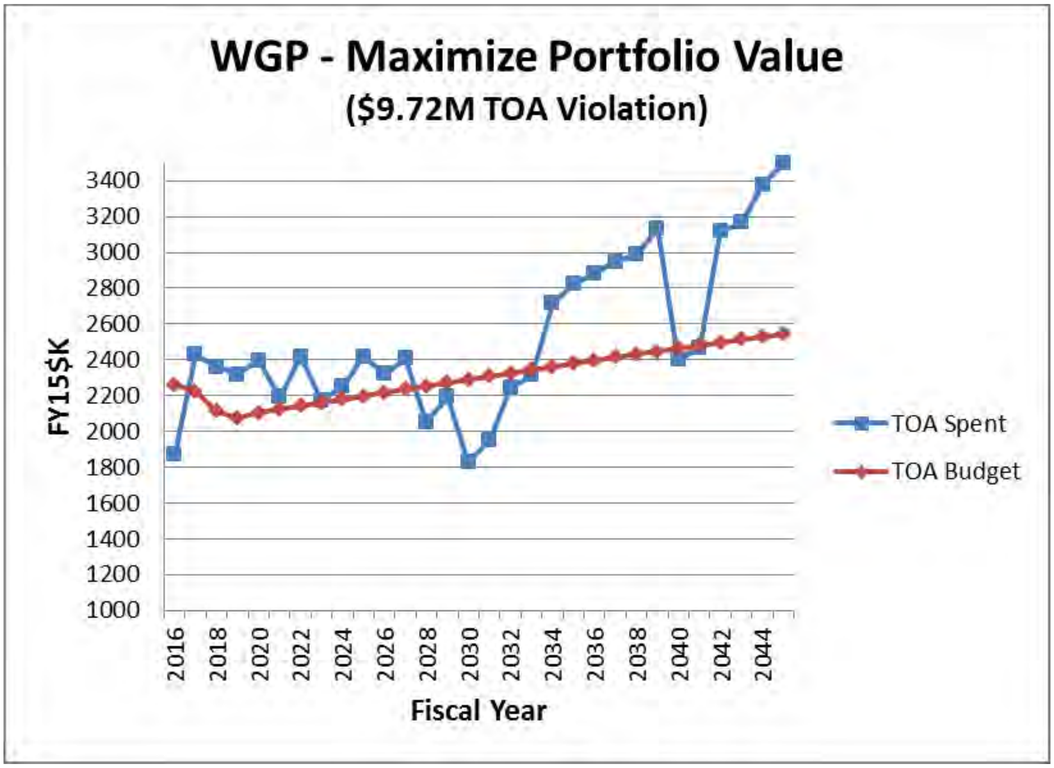

Figure 13. TOA spending for the WGP model maximizing portfolio value and project procurement.

Our results from varying the goal priorities for the WGP model highlight the fact that the best achievement level for each goal is attained when that goal is given nearly all of the priority. This confirms that the WGP model is operating as expected and producing valid results. Our model results also show the flexibility of the WGP approach by demonstrating the model's ability to allow for tradeoffs between investment goals and priorities. This is in contrast to the BK model, which optimized a single objective (portfolio value) subject to budget constraint.

D. WGPwPT MODEL

We now enhance the WGP model to incorporate platform tracking. For the WGPwPT, we examine the projects at the platform level, allowing the model to spread project procurement over several time periods. We use a 30-year time horizon and 68 projects made up of 612 total platforms. We use 4,532 decision variables, including 4,080 integer decision variables for procurement and retirement decisions, and 452 positive

decision variables for goal deviations (60 each for budget, inventory, and portfolio value violations and 136 each for procurement and retirement violations). The WGPwPT model uses 8386 constraints, including 226 elastic constraints (30 each for budget, inventory, and portfolio value and 68 each for procurement and retirement).

1. Data

Procurement Cost: We use notional estimates for procurement costs. These costs represent money budgeted for platform procurement and RDT&E in a given year. These amounts are budgeted over the 30-year planning horizon with no distinction between procurement and RDT&E amounts. The procurement cost data used for the WGPwPT model differs from the data used for the BK and WGP models because the amounts are per platform costs versus per project. The platform cost data is provided in Appendix E.

Budget: We use the same TOA budget data that we used for the BK and WGP models. These amounts are shown in Appendix B.

Platform Inventory and Value: For the WGPwPT, each project is composed of a desired inventory of platforms, $reqinventory_{pt}$. The desired inventory of platforms for each project is listed in Appendix D. We set $startinv_p$ and $authinventory_{pt}$ levels equal to $reqinventory_{pt}$ levels, reflecting a situation in which our initial inventory is sufficient, but we have the ability of upgrade our capabilities over time .

We calculate the platform values using the same randomly generated numbers between 0 and 5 used for the BK and WGP models. To determine $fixedcontrib_p$, we divide the project value by $reqinventory_{pt}$ (e.g., project one has a value of five and has a desired inventory of nine platforms, so each platform has a value of 5/9). These values are shown in Appendix D.

Cumulative Procurement and Retirement Goals: We use notional cumulative procurement and retirement goals for the WGPwPT model to allow for a flexible procurement schedule. For example, if Proj1 requires 30 platforms to be procured over 15 years beginning in FY31, we list the increasing procurement goal over the 15 years in increments equal to the yearly maximum procurement for that platform, reaching the

target of 30 platforms on or before the 15th year. This allows the model to spread procurement out over the entire planning horizon. We set the $procaspire_p$ equal to $reqinventory_{pt}$. The cumulative procurement values are provided in Appendix F.

In addition to cumulative procurement goals, we also set yearly maximum platform procurement ($maxprojproc_{pt}$) levels to prevent the model from making unrealistic choices to procure the entire $procaspire_p$ in one year. The $maxprojproc_{pt}$ values are provided in Appendix G.

Identical to the procurement data, we use cumulative retirement goals to allow for a flexible retirement schedule. We set $retaspire_p$ equal to $procaspire_p$. In other words, for every platform procured, one is retired. The cumulative retirement goals are identical to the cumulative procurement goals shown in Appendix F.

In addition to cumulative retirement goals, we also set yearly maximum platform retirement ($maxprojret_{pt}$) levels. The $maxprojret_{pt}$ values are equal to the $maxprojproc_{pt}$ values shown in Appendix G.

2. Analysis of Results

The power of the WGPwPT is found in the ability of the model to schedule platform procurement and retirement early or late to accommodate varying procurement requirements and priorities. The model also provides greater flexibility because procurements are made at the platform level as opposed to the project level, avoiding the all-or-nothing decision.

We validate the WGPwPT model by analyzing the effect of varying goal priorities on the goals of maximizing platform procurement and portfolio value and minimizing TOA budget violations. We perform model runs using three different goal weighting profiles: (1) baseline with goal priorities weighted equally, (2) higher priority given to minimizing budget violations, and (3) higher priority given to maximizing portfolio value and platform procurement. The metric we used for each of the goals is defined in Table 5. For each run, we gave the prioritized goals a weight of 10 and the other goals a negligible

weight of .001. We use the original baseline budget and hold all other model parameters constant. The resulting objective values for each of the runs are shown in Table 7.

Table 7. Results for WGPwPT model varying goal priorities.

Metric	Baseline Goals Weighted Equally	Minimize Budget Violations	Maximize Portfolio Value
Total Portfolio Value (Maximum Possible: 3000)	3000	3000	3000
Percentage of TOA Violations	1.60%	1.34%	7.42%
Percentage of Funded Platforms	98.96%	97.92%	100%

Our analysis of the investment strategy recommended by the WGPwPT baseline model reveals large TOA under-expenditures in FY16, FY30, and FY31 accounting for 77.5% of the $1.13 million TOA violation over 30 years. This is an improvement of $800 thousand over the WGP baseline model. The WGPwPT baseline model recommends not funding 19 platforms. This is an improvement over the BK and WGP baseline models, but we cannot make a one to one comparison because the WGPwPT model procurement numbers are expressed in terms of platforms as opposed to projects. In addition to producing improved results for both TOA spending and platforms funded, the WGPwPT baseline model maximizes the portfolio the portfolio value. Figures 14 and 15 provide a summary of the results for the WGPwPT baseline model.

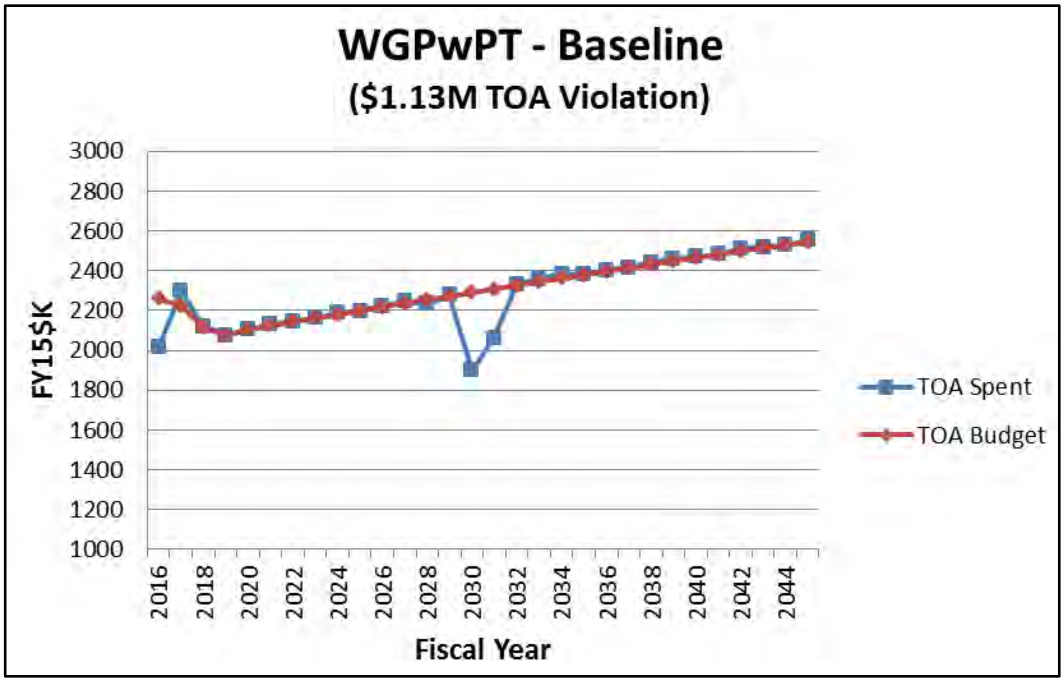

Figure 14. TOA spending for the WGPwPT baseline model.

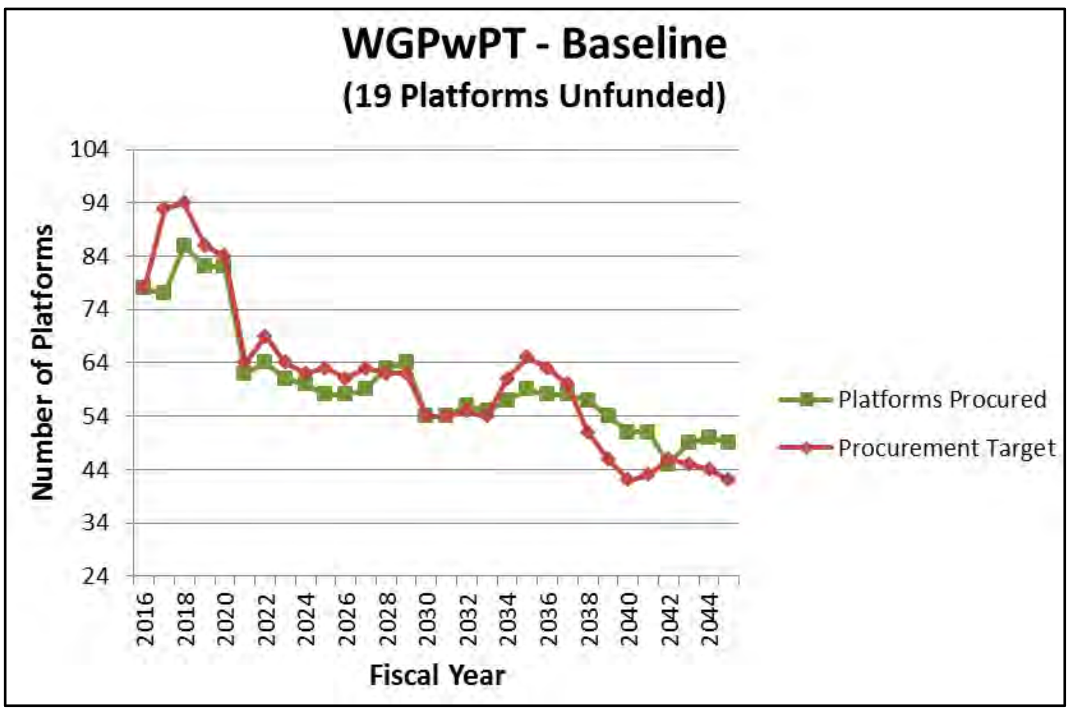

Figure 15. Platform funding for the WGPwPT baseline model.

When we prioritize the goal to minimize budget violations, the WGPwPT model produces a total TOA violation of $929 thousand over the 30-year planning horizon. This is an improvement of $761 thousand over the WGP baseline and $201 thousand over the WGPwPT baseline, but comes at a cost of not funding 38 platforms, twice as many as the WGPwPT baseline. Figures 16 and 17 show the TOA spending and platform funding results for the WGPwPT model minimizing budget violations.

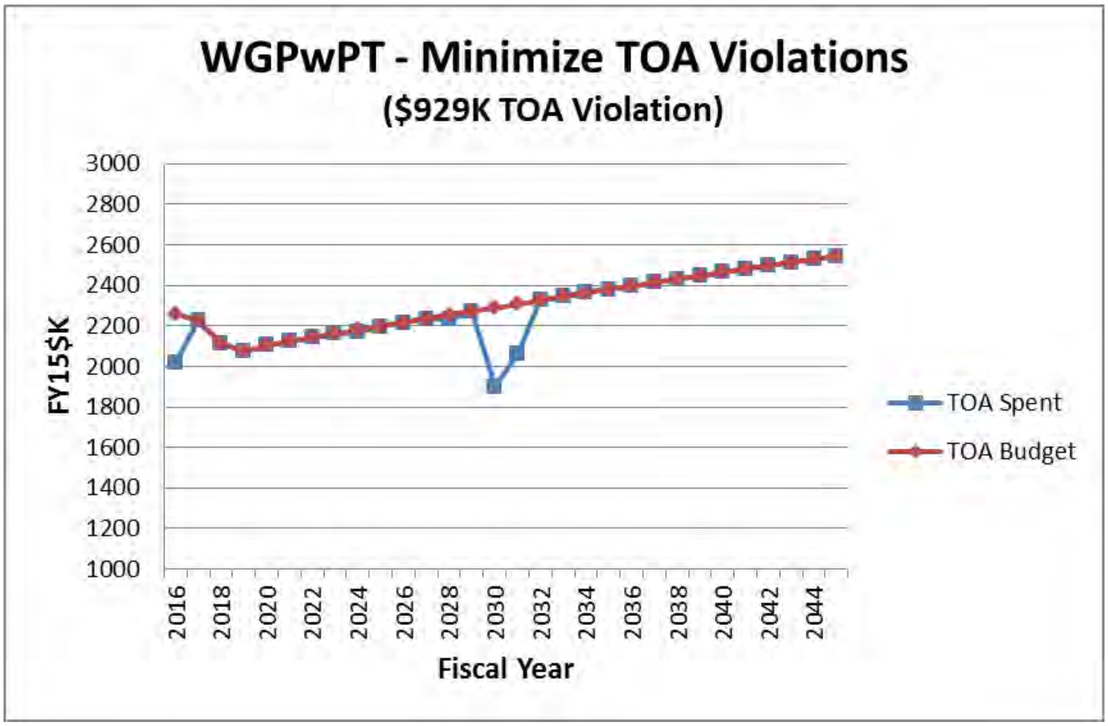

Figure 16. TOA spending for the WGPwPT model minimizing budget violations.

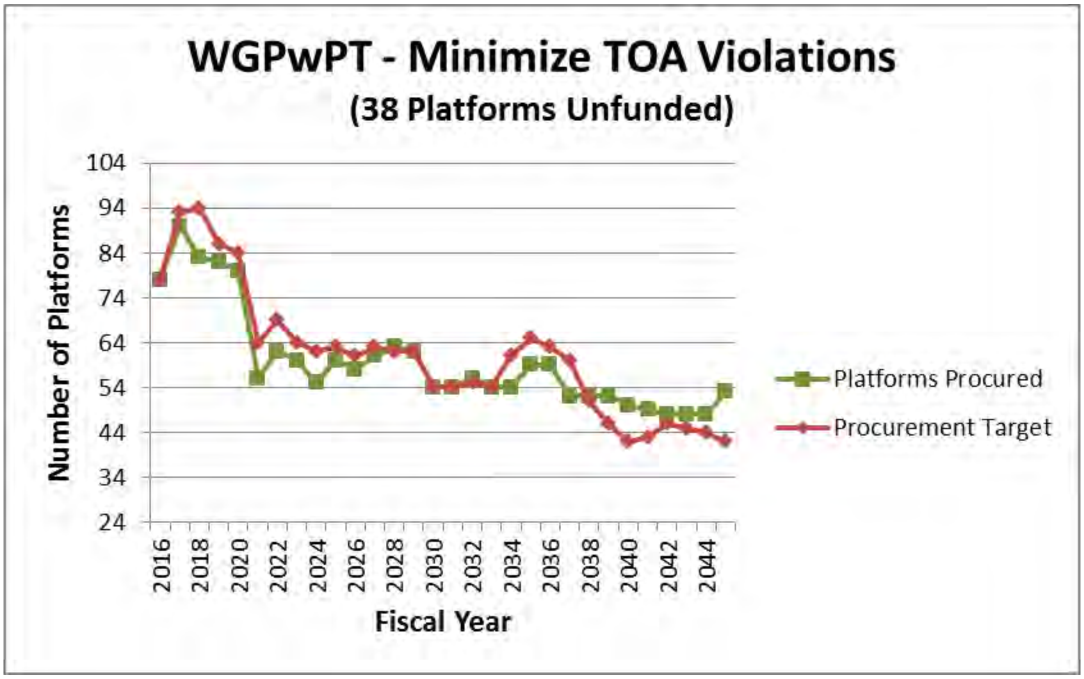

Figure 17. Platform funding for the WGPwPT model minimizing budget violations.

When we prioritize the goals to maximize portfolio value and project procurement, the WGPwPT model produces a total TOA budget violation of $5.14 million over the 30-year planning horizon. This is an increase of $4.01 million over the WGPwPT baseline. The increase in TOA allows for all of the platforms to be procured. Figures 18 and 19 show the TOA spending and platform funding results for the WGPwPT model maximizing portfolio value and platform procurement.

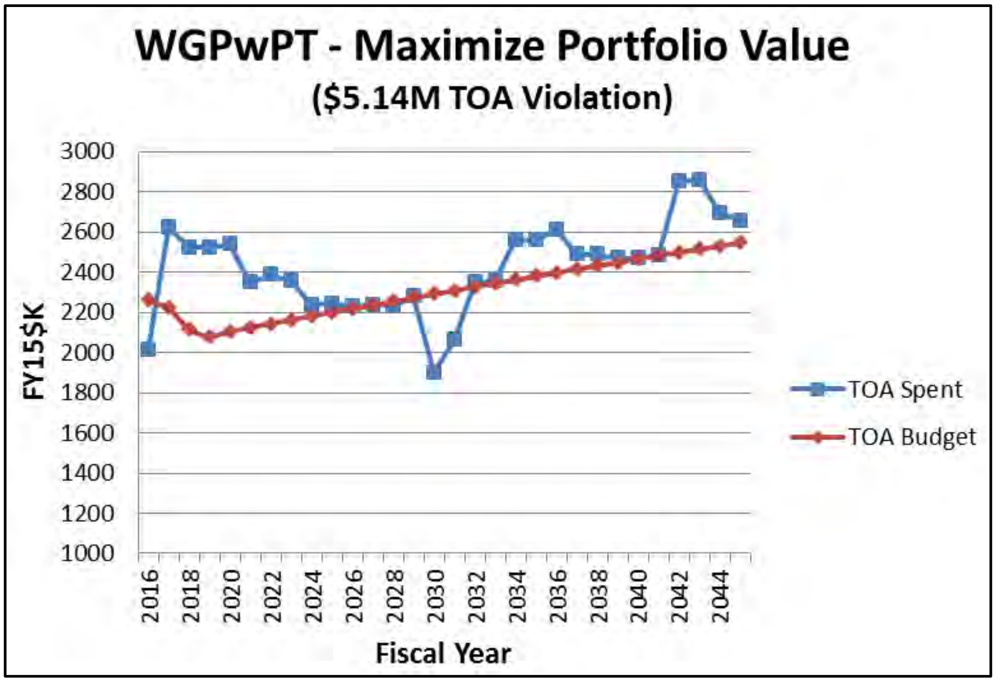

Figure 18. TOA spending for the WGPwPT model maximizing portfolio value and platform procurement.

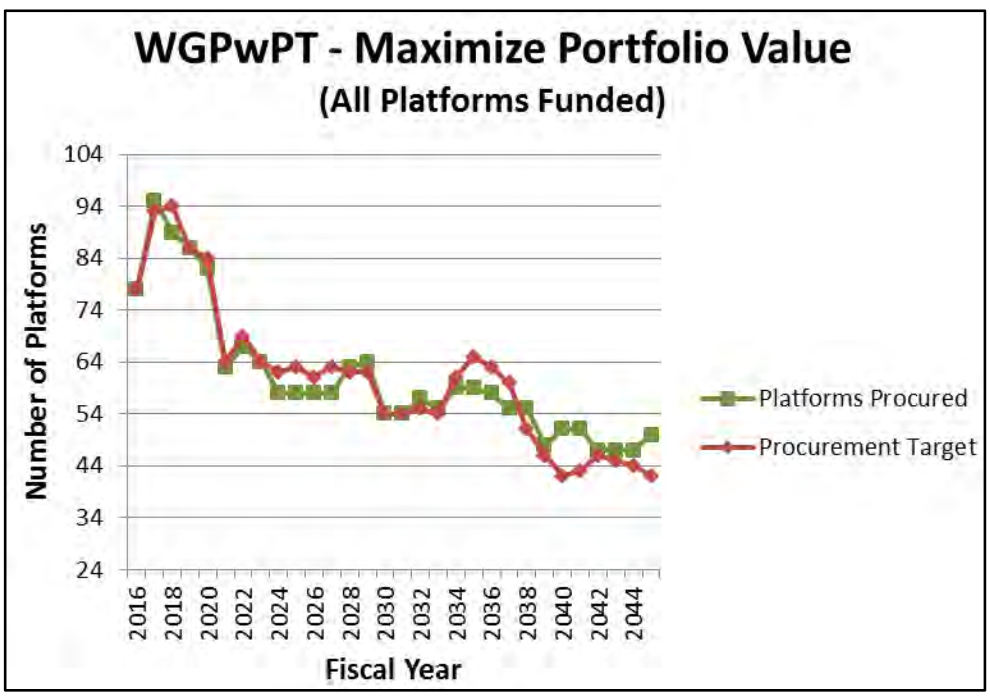

Figure 19. Platform funding for the WGPwPT model maximizing portfolio value and platform procurement.

Our results from varying the goal priorities for the WGPwPT highlight the benefit of cumulative procurement and retirement goals and further emphasize the flexibility of goal programming. With cumulative procurement and retirement goals, the WGPwPT model allows for over and under violations in individual years, making optimal use of the available TOA budget. The critical insight we derive from the WGPwPT model results is that not only does the model produce the best overall funding strategy; it balances platform procurement and retirement decisions, maximizing portfolio value. This ensures there are no capability gaps over the planning horizon.

V. CONCLUSIONS AND RECOMMENDATIONS

We formulated and analyzed three proof-of-principle optimization models for capital planning: the Binary Knapsack (BK) model, the Weighted Goal Programming Model (WGP) model, and the Weighted Goal Programming with Platform Tracking (WGPwPT) model. Our results show that the WGPwPT model produces the best overall funding strategy; it balances platform procurement and retirement decisions, maximizing portfolio value. With cumulative procurement and retirement goals, the WGPwPT model allows for over and under violations in individual years, making optimal use of the available TOA budget. The WGPwPT's higher modeling fidelity ensures there are no capability gaps over the planning horizon, but it comes at the cost of additional data requirements and flexibility in the procurement process. Assuming the necessary data and flexibility exist, we recommend that USSOCOM incorporate the WGPwPT optimization model into the LRCPT as an improved method for examining the impact of long-range investments.

Since September 11, 2001, USSOCOM has spent nearly $70 billion on operations and maintenance (Weisgerber, 2014). This is over three times the amount spent on procurement and RDT&E. Since the WGPwPT model only looks at combined procurement and RDT&E cost, we recommend that the WGPwPT model be enhanced to incorporate operations and maintenance costs.

Furthermore, in the WGPwPT model, procurement and retirement decisions are based solely on inventory levels and do not account for dependencies between platforms. Additionally, portfolio value does not account for increased value achieved by combining different platforms. We recommend further study to examine platform dependencies and synergistic effects (Brown, Dell, & Newman, 2004).

Finally, although the WGPwPT model output is easily analyzed with a spreadsheet, model manipulation requires experience with Excel OpenSolver and GAMS. We believe a simple graphical user interface is required to make the model user friendly for the average analyst.

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APPENDIX A. $fixedcost_{pt}$ FOR BK AND WGP

	Project Fixed Cost (in $1,000s)														
	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Project (*p*)															
proj1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj2	0	44	45	46	47	48	49	50	52	54	0	0	0	56	58
proj3	0	295	304	313	322	332	342	352	363	374	385	397	0	0	0
proj4	31	32	33	34	35	0	0	36	37	38	39	40	41	42	0
proj5	0	0	0	0	0	0	168	173	178	183	188	194	200	206	0
proj6	20	21	22	23	24	0	0	0	25	26	27	28	29	30	0
proj7	15	16	16	17	18	19	20	21	22	23	24	25	26	27	28
proj8	0	74	74	74	74	0	0	0	0	0	0	0	0	0	0
proj9	0	51	51	51	51	0	0	0	0	0	0	0	0	0	0
proj10	14	14	15	16	17	18	19	20	21	22	23	24	25	26	27
proj11	17	18	0	0	0	0	0	0	0	0	0	0	19	20	21
proj12	30	31	32	33	34	35	36	0	0	0	37	38	39	40	41
proj13	19	0	0	0	20	21	22	23	0	0	0	24	25	26	27
proj14	10	10	10	10	10	10	10	10	0	0	0	0	0	0	0
proj15	36	37	38	0	0	0	0	0	0	0	0	0	0	0	0
proj16	38	39	40	41	42	0	0	0	0	0	0	0	0	43	44
proj17	15	16	17	18	19	20	21	22	23	0	0	0	0	0	0
proj18	10	11	12	13	14	15	16	17	18	19	20	21	0	0	0
proj19	12	13	14	0	0	0	0	0	0	0	0	0	0	0	0
proj20	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
proj21	0	16	17	18	19	20	21	22	23	24	25	26	27	28	29
proj22	93	96	0	0	0	0	0	0	0	0	0	0	0	0	0
proj23	104	107	110	113	116	119	123	127	131	135	0	0	0	0	0
proj24	30	0	31	32	33	34	35	36	37	38	39	40	41	42	43
proj25	30	31	32	33	34	0	0	0	35	36	37	38	39	40	41
proj26	192	198	204	210	216	222	229	0	0	0	0	0	0	0	0
proj27	0	0	0	0	0	0	0	0	0	127	131	135	139	143	0
proj28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj29	120	124	128	132	136	140	144	148	152	157	162	167	172	177	182
proj30	0	43	44	45	46	0	0	0	0	0	0	0	0	0	0
proj31	26	26	27	27	28	28	29	30	30	31	31	32	33	33	34
proj32	20	20	21	21	22	22	23	23	23	24	24	25	25	26	26
proj33	8	8	8	8	9	9	9	9	9	10	10	10	10	10	11
proj34	6	7	7	7	7	7	7	7	7	8	8	8	8	8	8
proj35	8	9	9	9	9	9	9	10	10	10	10	10	11	11	11
proj36	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
proj37	29	30	30	31	32	32	33	34	34	35	36	36	37	38	39
proj38	77	79	80	82	84	85	87	89	90	92	94	96	98	100	102
proj39	7	8	8	8	8	8	8	9	9	9	9	9	9	10	10
proj40	7	7	7	8	8	8	8	8	8	8	9	9	9	9	9
proj41	30	31	31	32	32	33	34	34	35	36	37	37	38	39	40
proj42	19	19	19	20	20	21	21	22	22	22	23	23	24	24	25
proj43	13	13	14	14	14	14	15	15	15	16	16	16	16	17	17
proj44	20	20	21	21	22	22	23	23	23	24	24	25	25	26	26
proj45	24	24	25	25	26	26	27	27	28	28	29	30	30	31	31
proj46	7	7	7	7	7	7	7	8	8	8	8	8	8	9	9
proj47	28	29	29	30	30	31	32	32	33	33	34	35	36	26	37
proj48	69	69	69	69	69	69	69	0	0	0	0	0	0	0	0
proj49	63	64	65	66	68	69	70	72	73	75	76	78	79	81	83
proj50	32	33	33	34	35	35	36	37	37	38	39	40	41	41	42
proj51	13	13	14	14	14	14	15	15	15	16	16	16	16	17	17
proj52	5	5	5	5	5	6	6	6	6	6	6	6	6	6	7
proj53	11	11	11	12	12	12	12	13	13	13	13	14	14	14	15
proj54	20	20	21	21	22	22	23	23	23	24	24	25	25	26	26
proj55	20	20	21	21	22	22	23	23	23	24	24	25	25	26	26
proj56	67	74	68	62	63	74	75	77	78	80	81	83	85	86	88
proj57	12	14	13	11	12	14	14	14	14	15	15	15	16	16	16
proj58	42	46	43	39	40	46	47	48	49	50	51	52	53	54	56
proj59	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj60	16	18	17	15	16	18	18	19	19	20	20	20	21	21	22
proj61	12	13	12	11	11	13	13	14	14	14	14	15	15	15	16
proj62	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj63	112	124	114	105	107	124	126	129	132	134	137	140	142	145	148
proj64	6	6	6	5	5	6	6	6	6	7	7	7	7	7	7
proj65	98	108	100	91	93	108	110	112	114	117	119	121	124	126	129
proj66	33	37	34	31	32	37	37	38	39	40	41	41	42	43	44
proj67	9	10	9	8	8	10	10	10	10	10	10	11	11	11	11
proj68	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

	Project Fixed Cost (in $1,000s)														
	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
Project (*p*)															
proj1	182	187	193	199	205	211	217	224	231	0	0	0	0	0	0
proj2	60	62	64	66	0	0	0	0	68	70	72	74	76	78	0
proj3	0	0	0	0	0	0	0	0	0	0	0	409	421	434	447
proj4	0	0	43	44	45	46	47	48	49	0	0	0	50	52	54
proj5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj6	0	0	0	31	32	33	34	35	36	0	0	0	0	37	38
proj7	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
proj8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj10	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
proj11	22	23	0	0	0	0	0	0	0	0	0	0	24	25	26
proj12	42	0	0	0	0	43	44	45	46	47	48	0	0	0	0
proj13	0	0	0	28	29	30	31	0	0	0	32	33	34	35	0
proj14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj15	0	39	40	41	42	43	44	45	46	0	0	0	0	0	0
proj16	45	46	47	48	49	0	0	0	0	0	0	0	0	50	52
proj17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj18	0	0	0	0	0	0	0	0	22	23	24	25	26	27	28
proj19	0	0	0	0	15	16	17	18	0	0	0	0	0	0	0
proj20	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
proj21	0	0	0	0	0	0	0	0	0	0	30	31	32	33	34
proj22	0	0	0	0	99	102	105	108	111	0	0	0	0	0	0
proj23	0	0	0	139	143	147	151	156	161	166	171	176	181	186	192
proj24	44	45	46	47	48	49	50	52	54	56	58	60	62	64	66
proj25	0	0	0	42	43	44	45	46	47	48	0	0	0	49	50
proj26	0	0	0	0	0	0	0	0	0	0	0	236	243	250	258
proj27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	147
proj28	0	250	258	266	274	282	290	299	308	0	0	0	0	0	0
proj29	187	193	199	205	211	217	224	231	238	245	252	260	268	276	284
proj30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj31	35	35	36	37	38	38	39	40	41	41	42	43	44	45	46
proj32	27	27	28	29	29	30	30	31	32	32	33	33	34	35	36
proj33	11	11	11	11	12	12	12	12	13	13	13	13	14	14	14
proj34	9	9	9	9	9	10	10	10	10	10	11	11	11	11	11
proj35	11	12	12	12	12	12	13	13	13	14	14	14	14	15	15
proj36	61	62	63	64	66	67	68	70	71	72	74	75	77	78	80
proj37	39	40	41	42	43	43	44	45	46	47	48	49	50	51	52
proj38	104	106	108	110	112	115	117	119	122	124	127	129	132	134	137
proj39	10	10	10	11	11	11	11	11	12	12	12	12	13	13	13
proj40	10	10	10	10	10	11	11	11	11	11	12	12	12	12	13
proj41	40	41	42	43	44	45	45	46	47	48	49	50	51	52	53
proj42	25	26	26	27	27	28	28	29	30	30	31	31	32	33	33
proj43	17	18	18	19	19	19	20	20	21	21	21	22	22	23	23
proj44	27	27	28	29	29	30	30	31	32	32	33	33	34	35	36
proj45	32	33	33	34	35	35	36	37	38	38	39	40	41	41	42
proj46	9	9	9	9	10	10	10	10	10	11	11	11	11	11	12
proj47	38	38	39	40	41	42	42	43	44	45	46	47	48	49	50
proj48	0	0	0	103	103	103	103	103	103	103	103	103	0	0	0
proj49	84	86	88	89	91	93	95	97	99	101	103	105	107	109	111
proj50	43	44	45	46	47	48	49	49	50	51	52	54	55	56	57
proj51	17	18	18	19	19	19	20	20	21	21	21	22	22	23	23
proj52	7	7	7	7	7	7	8	8	8	8	8	8	9	9	9
proj53	15	15	15	16	16	16	17	17	17	18	18	18	19	19	20
proj54	27	27	28	29	29	30	30	31	32	32	33	33	34	35	36
proj55	27	27	28	29	29	30	30	31	32	32	33	33	34	35	36
proj56	90	92	93	95	97	99	101	103	105	107	109	112	114	116	118
proj57	17	17	17	18	18	18	19	19	19	20	20	21	21	21	22
proj58	57	58	59	60	61	63	64	65	66	68	69	70	72	73	75
proj59	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj60	22	23	23	23	24	24	25	25	26	26	27	27	28	29	29
proj61	16	16	17	17	17	18	18	18	19	19	19	20	20	21	21
proj62	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2
proj63	151	154	157	160	164	167	170	174	177	181	184	188	192	195	199
proj64	7	8	8	8	8	8	8	9	9	9	9	9	9	10	10
proj65	131	134	137	139	142	145	148	151	154	157	160	163	167	170	173
proj66	45	46	47	48	48	49	50	51	52	54	55	56	57	58	59
proj67	12	12	12	12	13	13	13	13	14	14	14	14	15	15	15
proj68	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

APPENDIX B. PLANNING HORIZON TOA BUDGET

Fiscal Year (t)	$budget_t$ (Thousands of Dollars)
FY16	2,260
FY17	2,225
FY18	2,115
FY19	2,075
FY20	2,104
FY21	2,123
FY22	2,142
FY23	2,161
FY24	2,180
FY25	2,198
FY26	2,217
FY27	2,235
FY28	2,254
FY29	2,272
FY30	2,290
FY31	2,308
FY32	2,326
FY33	2,344
FY34	2,362
FY35	2,379
FY36	2,397
FY37	2,414
FY38	2,431
FY39	2,448
FY40	2,465
FY41	2,481
FY42	2,498
FY43	2,514
FY44	2,529
FY45	2,545

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APPENDIX C. PROJECT VALUES FOR BK & WGP MODELS

Project (p)	$fixedcontrib_p$
Proj1	5
Proj2	5
Proj3	5
Proj4	5
Proj5	5
Proj6	5
Proj7	4
Proj8	4
Proj9	4
Proj10	3
Proj11	3
Proj12	3
Proj13	2
Proj14	2
Proj15	2
Proj16	2
Proj17	2
Proj18	2
Proj19	2
Proj20	3
Proj21	1
Proj22	1
Proj23	1
Proj24	1
Proj25	1
Proj26	1
Proj27	1
Proj28	1
Proj29	1
Proj30	1
Proj31	1
Proj32	1
Proj33	1
Proj34	1
Proj35	0.75
Proj36	0.75

Project (p)	$fixedcontrib_p$
Proj37	1
Proj38	1
Proj39	1
Proj40	0.5
Proj41	0.5
Proj42	1
Proj43	0.5
Proj44	0.5
Proj45	1
Proj46	1
Proj47	0.8
Proj48	1
Proj49	0.5
Proj50	0.5
Proj51	0.5
Proj52	0.5
Proj53	0.5
Proj54	0.5
Proj55	0.5
Proj56	0.5
Proj57	0.5
Proj58	0.5
Proj59	0.2
Proj60	0.2
Proj61	0.2
Proj62	0.2
Proj63	0.2
Proj64	0.2
Proj65	0.1
Proj66	0.1
Proj67	0.2
Proj68	0.1

APPENDIX D. WGPWPT INVENTORY AND VALUE DATA

Project (*p*)	Total Project Value	$reqinventory_{pt}$	$fixedcontrib_p$
Proj1	5	30	0.166666667
Proj2	5	18	0.277777778
Proj3	5	24	0.208333333
Proj4	5	25	0.2
Proj5	5	27	0.185185185
Proj6	5	25	0.2
Proj7	4	1	4
Proj8	4	16	0.25
Proj9	4	23	0.173913043
Proj10	3	1	3
Proj11	3	15	0.2
Proj12	3	29	0.103448276
Proj13	2	23	0.086956522
Proj14	2	25	0.08
Proj15	2	27	0.074074074
Proj16	2	24	0.083333333
Proj17	2	27	0.074074074
Proj18	2	20	0.1
Proj19	2	20	0.1
Proj20	3	1	3
Proj21	1	19	0.052631579
Proj22	1	19	0.052631579
Proj23	1	16	0.0625
Proj24	1	1	1
Proj25	1	16	0.0625
Proj26	1	20	0.05
Proj27	1	20	0.05
Proj28	1	16	0.0625
Proj29	1	1	1
Proj30	1	25	0.04
Proj31	1	1	1
Proj32	1	1	1
Proj33	1	1	1
Proj34	1	1	1
Proj35	0.75	1	0.75
Proj36	0.75	1	0.75

Project (p)	Total Project Value	$reqinventory_{pt}$	$fixedcontrib_p$
Proj37	1	1	1
Proj38	1	1	1
Proj39	1	1	1
Proj40	0.5	1	0.5
Proj41	0.5	1	0.5
Proj42	1	1	1
Proj43	0.5	1	0.5
Proj44	0.5	1	0.5
Proj45	1	1	1
Proj46	1	1	1
Proj47	0.8	1	0.8
Proj48	1	21	0.047619048
Proj49	0.5	1	0.5
Proj50	0.5	1	0.5
Proj51	0.5	1	0.5
Proj52	0.5	1	0.5
Proj53	0.5	1	0.5
Proj54	0.5	1	0.5
Proj55	0.5	1	0.5
Proj56	0.5	1	0.5
Proj57	0.5	1	0.5
Proj58	0.5	1	0.5
Proj59	0.2	1	0.2
Proj60	0.2	1	0.2
Proj61	0.2	1	0.2
Proj62	0.2	1	0.2
Proj63	0.2	1	0.2
Proj64	0.2	1	0.2
Proj65	0.1	1	0.1
Proj66	0.1	1	0.1
Proj67	0.2	1	0.2
Proj68	0.1	1	0.1

APPENDIX E. $fixedcost_{pt}$ FOR WGPwPT

	Platform Fixed Cost (in $1,000s)														
	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Project (*p*)															
proj1	55	55	55	55	55	55	55	55	55	55	55	55	55	55	55
proj2	44	44	45	46	47	48	49	50	52	54	54	54	54	56	58
proj3	184	184	190	196	201	207	214	220	227	234	241	248	248	248	248
proj4	28	29	30	31	32	32	32	33	34	34	35	36	37	38	38
proj5	50	50	50	50	50	50	50	51	53	54	56	57	59	61	61
proj6	15	16	17	17	18	18	18	18	19	20	20	21	22	23	23
proj7	15	16	16	17	18	19	20	21	22	23	24	25	26	27	28
proj8	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19
proj9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
proj10	14	14	15	16	17	18	19	20	21	22	23	24	25	26	27
proj11	11	12	12	12	12	12	12	12	12	12	12	12	13	13	14
proj12	20	21	21	22	23	23	24	24	24	24	25	25	26	27	27
proj13	14	14	14	14	15	16	16	17	17	17	17	18	19	19	20
proj14	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4
proj15	15	15	16	16	16	16	16	16	16	16	16	16	16	16	16
proj16	22	23	23	24	25	25	25	25	25	25	25	25	25	25	26
proj17	5	5	6	6	6	7	7	7	8	8	8	8	8	8	8
proj18	10	10	11	12	13	14	15	16	17	18	19	20	20	20	20
proj19	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5
proj20	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
proj21	16	16	17	18	19	20	21	22	23	24	25	26	27	28	29
proj22	34	35	35	35	35	35	35	35	35	35	35	35	35	35	35
proj23	76	78	80	82	85	87	90	93	96	99	99	99	99	99	99
proj24	30	30	31	32	33	34	35	36	37	38	39	40	41	42	43
proj25	23	24	24	25	26	26	26	26	27	27	28	29	30	30	31
proj26	105	109	112	115	119	122	126	126	126	126	126	126	126	126	126
proj27	38	38	38	38	38	38	38	38	38	38	39	41	42	43	43
proj28	125	125	125	125	125	125	125	125	125	125	125	125	125	125	125
proj29	120	124	128	132	136	140	144	148	152	157	162	167	172	177	182
proj30	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
proj31	26	26	27	27	28	28	29	30	30	31	31	32	33	33	34
proj32	20	20	21	21	22	22	23	23	23	24	24	25	25	26	26
proj33	8	8	8	8	9	9	9	9	9	10	10	10	10	10	11
proj34	6	7	7	7	7	7	7	7	7	8	8	8	8	8	8
proj35	8	9	9	9	9	9	9	10	10	10	10	10	11	11	11
proj36	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
proj37	29	30	30	31	32	32	33	34	34	35	36	36	37	38	39
proj38	77	79	80	82	84	85	87	89	90	92	94	96	98	100	102
proj39	7	8	8	8	8	8	8	9	9	9	9	9	9	10	10
proj40	7	7	7	8	8	8	8	8	8	8	9	9	9	9	9
proj41	30	31	31	32	32	33	34	34	35	36	37	37	38	39	40
proj42	19	19	19	20	20	21	21	22	22	22	23	23	24	24	25
proj43	13	13	14	14	14	14	15	15	15	16	16	16	16	17	17
proj44	20	20	21	21	22	22	23	23	23	24	24	25	25	26	26
proj45	24	24	25	25	26	26	27	27	28	28	29	30	30	31	31
proj46	7	7	7	7	7	7	7	8	8	8	8	8	8	9	9
proj47	28	29	29	30	30	31	32	32	33	33	34	35	36	26	37
proj48	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53
proj49	63	64	65	66	68	69	70	72	73	75	76	78	79	81	83
proj50	32	33	33	34	35	35	36	37	37	38	39	40	41	41	42
proj51	13	13	14	14	14	14	15	15	15	16	16	16	16	17	17
proj52	5	5	5	5	5	6	6	6	6	6	6	6	6	6	7
proj53	11	11	11	12	12	12	12	13	13	13	13	14	14	14	15
proj54	20	20	21	21	22	22	23	23	23	24	24	25	25	26	26
proj55	20	20	21	21	22	22	23	23	23	24	24	25	25	26	26
proj56	67	74	68	62	63	74	75	77	78	80	81	83	85	86	88
proj57	12	14	13	11	12	14	14	14	14	15	15	15	16	16	16
proj58	42	46	43	39	40	46	47	48	49	50	51	52	53	54	56
proj59	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj60	16	18	17	15	16	18	18	19	19	20	20	20	21	21	22
proj61	12	13	12	11	11	13	13	14	14	14	14	15	15	15	16
proj62	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj63	112	124	114	105	107	124	126	129	132	134	137	140	142	145	148
proj64	6	6	6	5	5	6	6	6	6	7	7	7	7	7	7
proj65	98	108	100	91	93	108	110	112	114	117	119	121	124	126	129
proj66	33	37	34	31	32	37	37	38	39	40	41	41	42	43	44
proj67	9	10	9	8	8	10	10	10	10	10	10	11	11	11	11
proj68	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

	Platform Fixed Cost (in $1,000s)														
	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
Project (*p*)															
proj1	55	56	58	60	62	63	65	57	69	69	69	69	69	69	69
proj2	60	62	64	66	66	66	66	66	68	70	72	74	76	78	78
proj3	248	248	248	248	248	248	248	248	248	248	248	256	263	271	279
proj4	38	38	39	40	41	42	43	44	45	45	45	45	45	47	49
proj5	61	61	61	61	61	61	61	61	61	61	61	61	61	61	61
proj6	23	23	23	23	24	25	26	27	27	27	27	27	27	28	29
proj7	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
proj8	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19
proj9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
proj10	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
proj11	15	15	15	15	15	15	15	15	15	15	15	15	16	17	17
proj12	28	28	28	28	28	29	29	30	31	31	32	32	32	32	32
proj13	20	20	20	21	22	22	23	23	23	23	24	24	25	26	26
proj14	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
proj15	16	16	16	17	17	18	18	18	19	19	19	19	19	19	19
proj16	26	27	27	28	29	29	29	29	29	29	29	29	29	29	30
proj17	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
proj18	20	20	20	20	20	20	20	20	21	22	23	24	25	26	27
proj19	5	5	5	5	5	6	6	6	6	6	6	6	6	6	6
proj20	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
proj21	29	29	29	29	29	29	29	29	29	29	30	31	32	33	34
proj22	35	35	35	35	37	38	39	40	41	41	41	41	41	41	41
proj23	99	99	99	102	104	110	110	115	118	121	125	128	132	136	140
proj24	44	45	46	47	48	49	50	52	54	56	58	60	62	64	66
proj25	31	31	31	32	33	33	34	35	36	37	37	37	37	37	38
proj26	126	126	126	126	126	126	126	126	126	126	126	130	134	137	142
proj27	43	43	43	43	43	43	43	43	43	43	43	43	43	43	44
proj28	125	125	129	133	137	141	145	149.5	154	154	154	154	154	154	154
proj29	187	193	199	205	211	217	224	231	238	245	252	260	268	276	284
proj30	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
proj31	35	35	36	37	38	38	39	40	41	41	42	43	44	45	46
proj32	27	27	28	29	29	30	30	31	32	32	33	33	34	35	36
proj33	11	11	11	11	12	12	12	12	13	13	13	13	14	14	14
proj34	9	9	9	9	9	10	10	10	10	10	11	11	11	11	11
proj35	11	12	12	12	12	12	13	13	13	14	14	14	14	15	15
proj36	61	62	63	64	66	67	68	70	71	72	74	75	77	78	80
proj37	39	40	41	42	43	43	44	45	46	47	48	49	50	51	52
proj38	104	106	108	110	112	115	117	119	122	124	127	129	132	134	137
proj39	10	10	10	11	11	11	11	11	12	12	12	12	13	13	13
proj40	10	10	10	10	10	11	11	11	11	11	12	12	12	12	13
proj41	40	41	42	43	44	45	45	46	47	48	49	50	51	52	53
proj42	25	26	26	27	27	28	28	29	30	30	31	31	32	33	33
proj43	17	18	18	19	19	19	20	20	21	21	21	22	22	23	23
proj44	27	27	28	29	29	30	30	31	32	32	33	33	34	35	36
proj45	32	33	33	34	35	35	36	37	38	38	39	40	41	41	42
proj46	9	9	9	9	10	10	10	10	10	11	11	11	11	11	12
proj47	38	38	39	40	41	42	42	43	44	45	46	47	48	49	50
proj48	53	53	53	79	79	79	79	79	79	79	79	79	79	79	79
proj49	84	86	88	89	91	93	95	97	99	101	103	105	107	109	111
proj50	43	44	45	46	47	48	49	49	50	51	52	54	55	56	57
proj51	17	18	18	19	19	19	20	20	21	21	21	22	22	23	23
proj52	7	7	7	7	7	7	8	8	8	8	8	8	9	9	9
proj53	15	15	15	16	16	16	17	17	17	18	18	18	19	19	20
proj54	27	27	28	29	29	30	30	31	32	32	33	33	34	35	36
proj55	27	27	28	29	29	30	30	31	32	32	33	33	34	35	36
proj56	90	92	93	95	97	99	101	103	105	107	109	112	114	116	118
proj57	17	17	17	18	18	18	19	19	19	20	20	21	21	21	22
proj58	57	58	59	60	61	63	64	65	66	68	69	70	72	73	75
proj59	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj60	22	23	23	23	24	24	25	25	26	26	27	27	28	29	29
proj61	16	16	17	17	17	18	18	18	19	19	19	20	20	21	21
proj62	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2
proj63	151	154	157	160	164	167	170	174	177	181	184	188	192	195	199
proj64	7	8	8	8	8	8	8	9	9	9	9	9	9	10	10
proj65	131	134	137	139	142	145	148	151	154	157	160	163	167	170	173
proj66	45	46	47	48	48	49	50	51	52	54	55	56	57	58	59
proj67	12	12	12	12	13	13	13	13	14	14	14	14	15	15	15
proj68	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

APPENDIX F. CUMULATIVE PROCUREMENT AND RETIREMENT GOALS FOR WGPWPT

Cumulative Procurement & Retirement Goals															
	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Project (p)															
proj1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj2	0	1	2	3	4	5	6	7	8	9	9	9	9	10	11
proj3	0	2	4	6	8	10	12	14	16	18	20	22	22	22	22
proj4	2	4	6	8	10	10	10	12	14	16	18	20	22	24	24
proj5	0	0	0	0	0	0	4	8	12	16	20	24	27	27	27
proj6	2	4	6	8	10	10	10	10	12	14	16	18	20	22	22
proj7	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj8	0	4	8	12	16	16	16	16	16	16	16	16	16	16	16
proj9	0	6	12	18	23	23	23	23	23	23	23	23	23	23	23
proj10	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj11	2	4	4	4	4	4	4	4	4	4	4	4	6	8	10
proj12	2	4	6	8	10	12	14	14	14	14	16	18	20	22	24
proj13	2	2	2	2	4	6	8	10	10	10	10	12	14	16	18
proj14	3	6	9	12	15	18	22	25	25	25	25	25	25	25	25
proj15	3	6	9	9	9	9	9	9	9	9	9	9	9	9	9
proj16	2	4	6	8	10	10	10	10	10	10	10	10	10	12	14
proj17	3	6	9	12	15	18	21	24	27	27	27	27	27	27	27
proj18	2	4	6	8	10	12	14	16	18	20	20	20	20	20	20
proj19	3	6	9	9	9	9	9	9	9	9	9	9	9	9	9
proj20	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj21	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14
proj22	3	6	6	6	6	6	6	6	6	6	6	6	6	6	6
proj23	1	2	3	4	5	6	7	8	9	10	10	10	10	10	10
proj24	2	0	4	6	8	10	12	14	16	18	20	22	24	26	28
proj25	1	2	3	4	5	5	5	5	6	7	8	9	10	11	12
proj26	2	4	6	8	10	12	14	14	14	14	14	14	14	14	14
proj27	0	0	0	0	0	0	0	0	0	4	8	12	16	20	20
proj28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj29	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj30	0	7	14	21	25	25	25	25	25	25	25	25	25	25	25
proj31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj32	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj33	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj34	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj35	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj36	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj37	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj38	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj39	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj40	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj41	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj42	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj43	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj44	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj45	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj46	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj47	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj48	2	4	6	8	10	12	14	14	14	14	14	14	14	14	14
proj49	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj50	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj51	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj52	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj53	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj54	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj55	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj56	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj57	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj58	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj59	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj60	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj61	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj62	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj63	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj64	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj65	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj66	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj67	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
proj68	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Cumulative Procurement & Retirement Goals															
	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
Project (*p*)															
proj1	4	8	12	16	20	24	28	30	30	30	30	30	30	30	30
proj2	12	13	14	15	15	15	15	15	16	17	18	18	18	18	18
proj3	22	22	22	22	22	22	22	22	22	22	22	24	24	24	24
proj4	24	24	25	25	25	25	25	25	25	25	25	25	25	25	25
proj5	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
proj6	22	22	22	24	25	25	25	25	25	25	25	25	25	25	25
proj7	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj8	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
proj9	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
proj10	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj11	12	14	14	14	14	14	14	14	14	14	14	14	15	15	15
proj12	26	26	26	26	26	28	29	29	29	29	29	29	29	29	29
proj13	18	18	18	20	22	23	23	23	23	23	23	23	23	23	23
proj14	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
proj15	9	12	15	18	21	24	27	27	27	27	27	27	27	27	27
proj16	16	18	20	22	24	24	24	24	24	24	24	24	24	24	24
proj17	27	27	27	27	27	27	27	27	27	27	27	27	27	27	27
proj18	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
proj19	9	9	9	9	12	15	18	20	20	20	20	20	20	20	20
proj20	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj21	14	14	14	14	14	14	14	14	14	14	15	16	17	18	19
proj22	6	6	6	6	9	12	15	18	19	19	19	19	19	19	19
proj23	10	10	10	11	12	13	14	15	16	16	16	16	16	16	16
proj24	30	30	30	30	30	30	30	30	30	30	30	30	30	30	30
proj25	12	12	12	13	14	15	16	16	16	16	16	16	16	16	16
proj26	14	14	14	14	14	14	14	14	14	14	14	16	18	20	20
proj27	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
proj28	0	2	4	6	8	10	12	14	16	16	16	16	16	16	16
proj29	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj30	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
proj31	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj32	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj33	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj34	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj35	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj36	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj37	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj38	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj39	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj40	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj41	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj42	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj43	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj44	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj45	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj46	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj47	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj48	14	14	14	16	18	20	21	21	21	21	21	21	21	21	21
proj49	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj50	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj51	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj52	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj53	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj54	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj55	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj56	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj57	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj58	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj59	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj60	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj61	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj62	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj63	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj64	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj65	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj66	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj67	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
proj68	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30

APPENDIX G. $maxprojproc_{pt}$ AND $maxprojret_{pt}$ VALUES FOR WGPwPT MODEL

	Maximum Yearly Procurement & Retirement														
Project (*p*)	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
proj1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj2	0	1	1	1	1	1	1	1	1	1	0	0	0	1	1
proj3	0	2	2	2	2	2	2	2	2	2	2	2	0	0	0
proj4	2	2	2	2	2	0	0	2	2	2	2	2	2	2	0
proj5	0	0	0	0	0	0	4	4	4	4	4	4	4	4	0
proj6	2	2	2	2	2	0	0	0	2	2	2	2	2	2	0
proj7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj8	0	4	4	4	4	0	0	0	0	0	0	0	0	0	0
proj9	0	6	6	6	6	0	0	0	0	0	0	0	0	0	0
proj10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj11	2	2	0	0	0	0	0	0	0	0	0	0	2	2	2
proj12	2	2	2	2	2	2	2	0	0	0	2	2	2	2	2
proj13	2	0	0	0	2	2	2	2	0	0	0	2	2	2	2
proj14	3	3	3	3	3	3	4	4	0	0	0	0	0	0	0
proj15	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0
proj16	2	2	2	2	2	0	0	0	0	0	0	0	0	2	2
proj17	3	3	3	3	3	3	3	3	3	0	0	0	0	0	0
proj18	2	2	2	2	2	2	2	2	2	2	2	2	0	0	0
proj19	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0
proj20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj21	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj22	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0
proj23	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
proj24	2	0	2	2	2	2	2	2	2	2	2	2	2	2	2
proj25	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1
proj26	2	2	2	2	2	2	2	0	0	0	0	0	0	0	0
proj27	0	0	0	0	0	0	0	0	0	4	4	4	4	4	0
proj28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj29	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj30	0	7	7	7	7	0	0	0	0	0	0	0	0	0	0
proj31	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj32	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj33	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj34	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj35	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj36	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj37	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj38	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj39	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj40	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj41	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj42	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj43	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj44	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj45	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj46	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj47	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj48	2	2	2	2	2	2	2	0	0	0	0	0	0	0	0
proj49	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj50	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj51	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj52	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj53	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj54	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj55	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj56	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj57	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj58	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj59	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj60	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj61	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj62	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj63	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj64	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj65	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj66	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj67	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj68	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

	Maximum Yearly Procurement & Retirement														
Project (p)	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045
proj1	4	4	4	4	4	4	4	4	4	0	0	0	0	0	0
proj2	1	1	1	1	0	0	0	0	1	1	1	1	1	1	0
proj3	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2
proj4	0	0	2	2	2	2	2	2	2	0	0	0	2	2	2
proj5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj6	0	0	0	2	2	2	2	2	2	0	0	0	0	2	2
proj7	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj10	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj11	2	2	0	0	0	0	0	0	0	0	0	0	2	2	2
proj12	2	0	0	0	0	2	2	2	2	2	2	0	0	0	0
proj13	0	0	0	2	2	2	2	0	0	0	2	2	2	2	0
proj14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj15	0	3	3	3	3	3	3	3	3	0	0	0	0	0	0
proj16	2	2	2	2	2	0	0	0	0	0	0	0	0	2	2
proj17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj18	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2
proj19	0	0	0	0	3	3	3	3	0	0	0	0	0	0	0
proj20	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj21	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
proj22	0	0	0	0	3	3	3	3	3	0	0	0	0	0	0
proj23	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
proj24	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
proj25	0	0	0	1	1	1	1	1	1	1	0	0	0	1	1
proj26	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2
proj27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
proj28	0	2	2	2	2	2	2	2	2	0	0	0	0	0	0
proj29	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
proj31	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj32	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj33	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj34	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj35	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj36	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj37	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj38	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj39	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj40	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj41	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj42	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj43	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj44	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj45	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj46	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj47	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj48	0	0	0	2	2	2	2	2	2	2	2	2	0	0	0
proj49	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj50	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj51	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj52	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj53	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj54	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj55	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj56	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj57	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj58	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj59	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj60	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj61	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj62	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj63	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj64	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj65	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj66	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj67	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
proj68	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

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